ISSN 1173-5996

Accounting for Sprinkler Effectiveness in Performance Based Design of Steel Buildings for Fire

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Fire Engineering Research Report 01/12

May 2001

This report was presented as a project report as part of the ME (Fire) Degree at the University of Canterbury

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ABSTRACT

For a specific range of building and occupancy types, this report examines the effectiveness of automatic sprinkler systems installed in New Zealand and Australia. The aim of the research is to quantify the likelihood of a fully developed fire occurring in sprinklered buildings. By deriving an annual probability of occurrence this can be compared with the accepted exceedance probabilities that exist for other limit state design actions for the design of steel structures.

Comprehensive data collated for the entire history of sprinkler installations in New Zealand and Australia is analysed to obtain conditional probabilities that confirm the effectiveness of sprinklers to control fires. These probabilities correspond to the likelihood of fully developed fire occurring being classified as an extremely unlikely event. Passive fire protection is normally provided to protect a structure against a fully developed fire. It is therefore suggested that certain types of structural steel frames in sprinklered buildings do not require passive fire protection to meet performance requirements of the Building Code.

The performance of steel frames without fire protection when exposed to fire following earthquake is assessed in a probabilistic framework. The likelihood of damage to the steel frame is not very different for the scenario of fire without earthquake.

This report also examines other aspects that affect sprinkler reliability, such as town main water supply, system isolation due to internal alterations and booster pump reliability. Most of these items do not have a major effect on sprinkler reliability.

Current literature describing the performance of steel framed multi-level buildings when subjected to fully developed fires is reviewed. The favourable behaviour of these real frames in natural fires confirms that the consequences are not usually serious if steel members without passive fire protection are exposed to severe fires.

ACKNOWLEDGEMENTS

Those who contributed in various ways to this research deserve mention and thanks.

- Ian Thomas and Ian Bennetts in particular, for providing information on statistical analysis of fires, feedback on reliability of sprinkler systems and water supplies and other information on the research programmes carried out by BHP Research, including the studies of the building at 140 William St, Melbourne. These two colleagues have provided my motivational interest in this subject for many years.

- John Fraser, for information on the history of sprinkler design and performance in New Zealand

- Charles Clifton for information and advice on the behaviour of steel buildings in fire and on current research in this field

- Andy Buchanan for his feedback, direction and helpful advice.

- Pat Roddick for assistance with literature, loans and documents

- HERA for information and support

- Others who provided valuable information and data include Mike Blanch (Metrowater), Richard Stewart (AFA Monitoring), Chris Mak (Wormald NZ), and Neil Gravestock (Insurance Council of New Zealand).

- My colleagues at Holmes Fire & Safety who supported this research in various ways

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1 INTRODUCTION

1.1 PERFORMANCE CRITERIA FOR STEEL STRUCTURES IN FIRE

Fundamental to this research is the need to define the performance required of structures in fire. In modern performance-based fire safety design, the objectives and functional requirements describe the necessary performance. How this performance is achieved is less important. Satisfying other criteria is irrelevant. Hence the focus of a performance-based design is not concerned with prescriptive solutions: they may be a means to an end, a way of achieving a performance objective, but satisfying prescriptive solutions alone is not an aim. By definition, one prescribed solution is not the only means of satisfying a performance objective and depending on how well matched the formulation of the prescriptive solution is to the actual problem, the solution may or may not be appropriate.

The New Zealand Building Code specifies objectives and functional requirements and performance criteria that need to be met. As long as these are met, then Building Code compliance is achieved, although there may also be other design requirements set by other interested parties that also need to be considered.

Because the research described in this report is concerned solely with the performance of steel structure in fire, the relevant performance criteria are only those relating to structural stability. The fact that structural stability is necessary to meet other performance criteria related to fire safety, is embodied in the performance criteria for the structure itself.

For reference, Clause C4 'Structural Stability During Fire' from the New Zealand Building Code is reproduced in Appendix A.

Because there are a number of possible solutions for satisfying a performance objective, there needs to be some way of ranking the outcomes so the best solutions can be identified. In practical terms, if the desired level of performance is reached then the usual criteria most often used to rank outcomes are (not necessarily in this order):

1. cost (capital cost; maintenance cost)

2. practicality/ease of construction

3. impact on functionality, ease of maintenance

4. aesthetics, impact on architecture

1.2 OBJECTIVE OF THIS RESEARCH PROJECT

Traditionally, steel structures have been protected from the effects of fire by applying insulative fire protection, but in New Zealand and Australia the performance of automatic sprinkler systems to control the growth and spread of fire appears to be very successful.

If the sprinkler systems are inherently very reliable, then there is a low probability of a fire growing to a size and severity that affects the steel structure of a building.

The research described in this report assesses the likely performance of steel structure in a sprinklered building in the event of fire. In particular, this research reviews the situations in which the sprinkler system may not function as intended to determine whether it is also necessary to provide passive fire protection to steel structure to comply with the performance-based design criteria of the New Zealand Building Code. In assessing the reliability of sprinklers, the features which contribute to sprinkler reliability are also examined. This provides an alternative means of quantifying sprinkler reliability to gauge whether or not a claim of high reliability and effectiveness is justified.

Fundamentally, this report is concerned with the probability of structural collapse. In terms of fire safety, and specifically life safety, the frequency of multiple deaths caused by fire spread has been far greater than from structural collapse, so the aspects of fire design discussed herein are not significant contributors to the life safety threat from fire.

1.3 SCOPE OF APPLICATION OF THIS RESEARCH

This research report applies to sprinklered buildings. In this context this means buildings protected with an automatic sprinkler system, designed and installed in accordance with sprinkler standards current at the time of installation, at least to the extent of the requirements in the standard that directly affect the ability of the system to activate and control a fire. The performance and reliability of the sprinkler systems noted in this report assumes that sprinkler systems are appropriately maintained.

From a sprinkler design and installation viewpoint, buildings containing storage, manufacturing and industrial occupancies are a relatively specialised subset of buildings in general. The flammability, fire load, quantity and distribution of goods contained in these buildings is often highly variable, ranging from metal fabrication to manufacture and storage of furniture and foam mattresses. The way goods are stored also varies: on pallets in racks, on shelves or simply as high-piled storage. The buildings themselves usually have a high ceiling (6 metres or more above the floor).

For these reasons, it is difficult to classify these various occupancies in terms of fire risk. Also, for these reasons the sprinkler effectiveness is more variable because there are greater risks and consequences of:

- a change in occupancy hence change in fire load and hazard from that for which the sprinkler system was designed
- inappropriate storage practices, such as storing too close to sprinklers or storing too much of the wrong type of product or adversely changing the way in which product is packaged

The buildings are almost always single storey and therefore exposed steel structure is seldom required to have passive fire protection to satisfy New Zealand Building Code requirements. For all of these reasons, these types of occupancies are excluded from the scope of this report. This report is interested in examining the high reliability and effectiveness of sprinklers used in the other common building occupancies with the intent of accounting for this beneficial performance in a risk assessment model for performance-based design.

Therefore, while not exclusively applicable to multi-level buildings (more than one floor) this research assumes occupancy types and fire loads normally associated with multi-level construction. This is not intended to exclude single level buildings but the types of high fire loads, particularly those associated with manufacturing and storage found only in single level buildings, are beyond the scope of this research. Further information on the types of occupancies and building uses which are included and excluded are given in the body of this report.

The findings of this report are applicable to the performance of steel structures in fire as stated and cannot be assumed to apply to other aspects of fire safety (such as other passive or active fire safety systems).

Similarly, the application of the results of this research cannot automatically be applied to other structural materials. This is because the redundancy and performance (of steel structure) in fire for various extreme scenarios has been considered. Also, in other structural materials there are different methods of designing and constructing structures and differences in the response to fire. Consequences of failure and redundancy also affect performance in fire for other structural materials. Structural systems will not necessarily be the same in other materials as for steel structures. Future research is needed to ascertain whether the results can be extrapolated in this way.

Other assumptions that have been made in this report include:

- Assessment of structural performance is based on exposure to a natural/real fire (not the 'standard' fire) i.e. a natural fire safety concept

- The steel structure has been designed in accordance with approved verification methods e.g. the New Zealand and Australian Steel Structures Standards NZS3404:1997, AS4100:1998, and previous versions. Hence the adequacy of the structure for compliance with other (non-fire) Building Code performance requirements is assumed. This report may not be applicable to cold-formed steel structures and is generally not applicable to light gauge steel members (steel element thickness outside the scope of the standards listed above).

2 INTERACTION BETWEEN SPRINKLERS AND STRUCTURE PERFORMANCE IN FIRE – AN OVERVIEW

2.1 INTRODUCTION

At face value, assessing the impact of sprinklers on the performance of steel structure in fire appears to be simple. It might appear obvious that either sprinklers have nothing to do with structural performance – they are two separate, independent, fire safety sub-systems (in which case no benefit can be attributed) or that sprinklers are assumed to operate to effectively control and suppress a fire on all occasions throughout the life of the structure (in which case one might assume they offer a complete trade-off against any adverse effects of fire on the structure).

However, an assessment in either of the above terms is overly simplistic. Closer inspection reveals that there are a number of factors which influence this problem and some of their inter-relationships are complex. A rational engineering analysis of these inter-relationships is needed to provide a credible basis for accounting for any benefit due to sprinklers on the performance of the structure.

Resolving this is essentially an issue of establishing adequate performance of steel structure in fire. In a performance-based design framework, adequate performance is established in probabilistic terms. This is usually expressed as a risk or probability of a particular limit state being exceeded.

To provide a uniform level of risk over a range of structural load combinations, materials and failure modes, target values for the safety index (a measure of structural reliability) have been used as the basis for structural design codes. For the design of structures to resist the effects of fire the same measure for structural reliability applies, as we are concerned principally with the performance of the structure, as distinct from other aspects of fire safety.

Therefore, the probability of the structural limit state being exceeded due to the effects of fire can be compared with the target value for structural reliability that applies to other limit states.

Accordingly, the limit state problem as described above can also be expressed in probabilistic terms.

To enable general design solutions to be developed from this research a number of simplifying assumptions were made. For example, in the probabilistic assessment model, it was assumed that if a fire is not controlled by sprinkler system that it grows to a size and severity that threatens structural stability.

2.2 FRAMEWORK FOR PROBABILISTIC ASSESSMENT

In this research a performance-based design approach has been used. In formulating a design approach that will achieve the desired performance objectives it is implied that there is always a finite risk of this not occurring. This can be regarded as the risk of 'failure'. With all design approaches, achieving a performance objective cannot be guaranteed, but as long as the risk of failing to achieve the desired performance is suitably low, then this is regarded as acceptable. The adequacy of any design to satisfy the performance objectives can therefore be assessed in probabilistic terms.

In structural design to current international limit state design standards, the risk of 'failure' is well established. This is discussed in more detail in section 4.2 of this report. In this report these criteria are also used as a benchmark for assessing adequate performance when accounting for the influence of sprinklers on the performance of steel structure in fire.

A design solution is regarded as acceptable if the probability of the structure not performing adequately in fire is lower than the target probabilities described later in this report.

Inadequate structural performance in fire is the outcome of two possible scenarios:

1. a structure of inadequate design subjected to a relatively small fire; here the predominant cause of failure is the original design of the structure (structural reliability much less than the accepted minimum value) giving rise to structural performance worse than expected under a set of specified fire conditions.

2. a structure of 'normal' design subjected to a fire severity sufficient to cause unacceptable performance.

Scenario 1 is not considered in this report because it is assumed that the design of the structure complies with all other (non-fire) aspects of structural design. Hence the adequacy of the structure (for compliance with other Building Code performance requirements) is assumed. Some aspects of structural reliability that are relevant to this scenario are discussed by Wong (1999).

For scenario 2 there are a number of factors that contribute to the likelihood of this occurring:

a) the need to be able to quantify the fire characteristics that would induce inadequate structural performance (this is linked, of course, to knowing how the structure will respond to a given fire scenario).

b) the probability of fire start and consequent fire growth (influenced by occupancy type), taking into account the fact that not all fire starts result in sustained burning

c) the probability that a fire progresses past the smouldering stage to flaming combustion and then develops to a size that requires sprinkler activation to control further fire growth

d) the probability that the sprinklers have been designed, installed and tested so that they have the ability to activate and discharge water effectively

e) the probability that the water supply is of adequate flowrate and pressure so that water is actually discharged as intended

f) the probability of sprinklers activating and controlling a fire

These factors can be incorporated into an event tree analysis. Where individual probabilities can be determined these have been used to derive an overall probability of occurrence of inadequate structural performance in a sprinklered building. This is discussed in section 10.1.

The response of the steel structure when subjected to unfavourable fire conditions is an important influence on the outcome of whether or not performance objectives are satisfied. However, this is also the most variable parameter in general design situations in the same way that the routine structural design is a tailor-made solution for each project. Results also depend on the modelling of fire temperatures and heat transfer models for the steel members to determine steel temperatures and consequently the response of the structure.

2.3 FACTORS INFLUENCING STRUCTURAL RELIABILITY

Putting aside the issue of general design of steel structures, which is beyond the scope of this report, and assuming that structures meet design requirements for the usual range of load combinations which do not involve fire, then the biggest influence on the reliability of structural performance is the fire itself. More accurately, it is the conditions around the structure that are generated by the fire that largely determine the structural response.

The effective operation of automatic sprinklers has the greatest influence on these fire conditions, so not surprisingly the reliability of sprinkler systems is the single most important feature that affects the outcome of this research.

For the research presented in this report, the overall effectiveness of sprinkler systems is also the primary focus. Although there are some components in a sprinkler system that are less reliable than others, most features in a sprinkler system have a very high reliability, evolved over many years of experience with fires and sprinklers. The other important component, which is usually beyond the control of a building owner, is the water supply. In this research, reliability of the water supply receives specific attention, to assess its influence on the overall results.

3 LITERATURE SURVEY

There are no direct links between sprinklers and structural performance other than the influence the performance of one system has on the other. Therefore the assessment considered in this research is only relevant in the context of performance-based design. For this reason, most research in this field has been conducted in the few countries where performance-based design is being implemented or exists already.

Not surprisingly, a survey of literature or research containing rational methods to account for the interaction between sprinklers and performance of steel structure in fire revealed very few references which have specifically addressed this topic.

Magnusson (1974) assessed the probability that a structural steel member will attain a certain limit state under the influence of a fully developed fire. This was a comprehensive probabilistic study, taking into account exposure of the steel structure to a time-temperature curve for a natural fire. However, this research assumed that the structure would be subjected to a fully developed fire and did not attempt to account for the effect of sprinkler activation on the likelihood of this occurring.

A study by Wong (1999) on the reliability of structural fire design reviewed a similar problem. In this case also, fully developed fire conditions were assumed and the influence of sprinklers was not taken into account.

The Design Guide for Structural Fire Safety (CIB W14, 1986) was perhaps one of the most comprehensive references for its time, describing methods for considering the exposure of structure to fire in terms of structural reliability. It concentrated on relating results from standard fire tests to performance in more generalised fire compartments. However, fully developed fire conditions are assumed and the effect of sprinklers on fire suppression is not covered.

Recent publications give design guidance on implementing performance-based analysis and design. Custer and Meacham (1997) and the Engineering Guide to Performance Based Fire Protection (SFPE, 2000) are both comprehensive in their coverage of this topic, and cover risk analysis, uncertainty and the use of statistical data for design purposes, but neither provides specific values to use in design.

The Fire Engineering Guidelines (FCRC, 1996) outlines a framework for design but also gives guidance on values to use for performance criteria, design input data. Similarly, the Guide to the Application of Fire Safety Engineering Principles published by British Standards (DD240, 1997), provides design guidance including data and equations to assist with engineered design solutions. These two publications are intended to be used as verification methods in a performance based regulatory framework, to establish acceptable levels of fire safety. Both publications also provide limited data on reliability and probability of failure for some fire safety systems. Unfortunately, the references for data are not always given and it appears that many may originate from the same source.

There are of course a number of references that contain recommendations for accounting for sprinklers in prescriptive design solutions. For example, Barnes (1997) reviewed the benefits (sprinkler 'trade-offs') that were embodied in the deemed-to-comply provisions of the New Zealand BIA Acceptable Solutions (BIA, 1995). Unfortunately, this review was fairly superficial and did not consider the wider issues of probability of failure of sprinklers and the consequence on structural performance. In that study, sprinkler reliability data used in a fault tree analysis was taken from Marryatt (1988). Schleich (1996) and DD240 (1997) both refer to nominal factors which are applied to account for the benefits of sprinkler systems when designing to prescriptive solutions. To account for the unlikely event of sprinklers not activating, Eurocode 1:Part 2.2 (ENV 1991-2-2:1995) allows a reduction factor to be applied to the nominal design fire load energy density. Others that have discussed sprinkler 'trade-offs' to varying degrees include Allen (1999a, 1999b) and Schulte (1999a, 1999b).

There are many references which describe research and design approaches accounting for the behaviour of complete steel frames in fully developed natural fires, as distinct from individual members subjected to the standard fire test. State of the art reports include Moore and Lennon (1997), Clifton and Forrest (1996), Eurofer (1990). These references are concerned only with the structural response to fire, not with the likelihood of the fire reaching a certain level of development.

Despite the lack of research specifically considering the indirect effect of sprinklers on performance of structures in fire, there are other papers published which contain related information useful to assess component reliabilities for use in a performance based design framework. The most useful and relevant research is by Marryatt (1971, 1988) who has collated comprehensive data on sprinkler performance over the first 100 years of sprinkler operation in Australia and New Zealand. The high reliability determined by this study is the main impetus for this research.

Fleming (1999) discusses the reliability of automatic sprinkler systems in the United States and how this data should be used in performance-based design. Bukowski et al (1999) have also published estimates of reliability of various components in fire safety systems which can be used in risk assessments and performance-based design. This paper includes a summary of reliability estimates from other researchers in the field. However, these papers do not discuss how this information should be used in design.

Researchers have published on topics related to risk assessment in the context of performance-based fire safety design, but most of these provide only a general overview, without much specific information or detail.

Yung and Hadjisophocleous (1999) describe the use of the FiRECAM risk assessment model using the reliability of sprinklers and fire alarms as variables. Data for the reliability of these components is assumed rather than examined. A four storey building is used as an example of how variations in reliability affect the expected risk to life. The results are intended to be comparative rather than absolute and there is no mention of effect of the fire on the structure. This is consistent with the life safety scenarios being considered but of little use for the research described in this report.

Studies closely aligned to the focus of this report are those carried out at various times by BHP Research in Australia. The comprehensive risk assessment carried out for the refurbishment of the building at 140 William St, Melbourne (Thomas et al, 1992a, 1992b) and other studies (Bennetts et al, 1995) were specifically carried out to assess the reliability of various components of fire safety systems, especially sprinklers, and to correlate this with the need to apply passive fire protection to steel structures.

Studies on water supply reliability for fire sprinklers have also been carried out by BHP Research in Australia as part of ongoing research into the fire behaviour and design of steel framed buildings. Results and comments have been reported in Bennetts et al (1995), Thomas et al (1992b) and Bennetts et al (1998). These include assessments of town main reliability as well as reliability of system components necessary for the delivery of water at the required pressure and flowrate, such as diesel and electric pumps.

Because solutions already exist which provide a solution for acceptable performance of structure in fire (e.g. applying passive fire protection), most of the discussion on the validity of sprinkler 'trade-offs' has concentrated on other aspects of fire safety. It is interesting to review these areas of discussion, even though they may not relate to structural performance or the need for passive fire protection, because they provide insight into the extent of reliance that some designers believe should be placed on sprinkler to control fires.

For example, many commentators such as Allen (1999a, 1999b), have discussed the merits of maintaining smoke detection and various forms of smoke control in sprinklered buildings, particularly high-rise buildings. Others such as Schulte (1999a, 1999b), argue that statistics for fire-related injuries and deaths in the United States support the view that sprinklers should form the basis of a trade-off for many more fire safety systems, including smoke detection; relaxation of requirements for egress/fire separations and others. Not surprisingly, others urge caution with this approach (Parnell et al, 1999).

Literature on the subject of fire following earthquakes was also reviewed because this scenario is considered by many to be one of the principle considerations for maintaining current levels of passive fire protection and not relying on sprinkler activation to control fires.

Robertson and Mehaffrey (1999) studied this issue in some detail, offering a rational approach which takes into account the low risk of such an event and suggests appropriate performance objectives. Botting and Buchanan (1998) have also reviewed the history of fires following earthquakes and summarise observations of damage to fire-related systems. Other references describing earthquake damage and fires following earthquakes have been reviewed. These are discussed in section 8 herein.

4 QUANTIFYING ACCEPTABLE PERFORMANCE

4.1 PROBABILISTIC ACCEPTANCE CRITERIA

4.1.1 Risk and Consequence

Assessment of risk is complex and must take into account a wide range of factors. But as well as the probability of an event happening, it is also necessary to account for the consequence of failure. In engineering this is often done as a matter of course.

For example, the failure mode of a structure may be ductile, predictable and give plenty of advance warning before a limit state is reached. This is far less serious than a failure which is sudden and catastrophic. Hence, although the risk of both types of failure occurring might be the same, they would be viewed differently because of the different consequences of failure.

Similarly with design of structures to resist fire. The probability of a structure reaching a given limit state may be small, especially if the building is sprinkler protected, but the consequence of sprinkler failure must be considered. It is not sufficient just to assume that if the probability is low then it is an acceptable risk. The risk may appear to be acceptably low but the consequence of it happening may change the perception. If it is too great then it may no longer be considered acceptable.

The perception of acceptable risk is also influenced by the degree of choice available to the person subjected to the threat. For example, people will subject themselves to significant risks (such as driving a car without wearing a seatbelt, cigarette smoking, etc) but consider the threat from various influences outside their direct control as unacceptable, even when these risks are very much lower (e.g. commercial air travel, building collapse due to earthquake, accident at a nuclear power station).

4.1.2 What is an acceptable level of risk?

How safe is safe?

It is important to correctly manage safety (Wolski et al, 1998), especially when the integration of various systems becomes more complex and the appropriate level of safety is only achieved when the interaction of a number of systems all occurs as designed.

As designs become less conservative and more tailored to each building, safety management becomes more important. In this context, management of safety means that all fire and occupant scenarios that have the potential to cause the loss of life or serious loss or damage to property have been identified and addressed.

There will always be a problem identifying tolerable levels of risk and appropriate levels of safety – there is no single answer. Perception plays a big part. However, quantitative risk assessment and reliability analyses can help to understand those aspects of the fire design that have the biggest impact on the safety of a design. More importantly, since the availability of the statistical data on the performance of fire safety systems is generally poor, techniques such as those used to assess structural reliability can be used to assess the change in reliability for different cases. The key word here is change – the paucity of data means that it is not appropriate to place high reliance on the absolute values obtained, but comparisons are valid.

In spite of the acknowledged difficulties in deciding on appropriate acceptance levels for performance-based design, the concepts of risk and reliability are common in engineering fields. Therefore, in this study, acceptable performance is assessed in terms of an acceptably low risk of failure.

Because we are concerned about the performance of the structure in fire, it is appropriate that the risk of "failure" (undesirable performance) be considered in similar terms to other forms of structural failure. The usual method for this assessment is concerned with structural reliability.

Structural reliability concepts are concerned with identifying the probability of a structure not performing as intended (i.e. failure), recognising that there is no such thing as absolute structural safety. Although relatively modern in the overall time frame of structural engineering, these methods have been in use for many decades and form the basis of modern limit state structural engineering codes and design methods.

4.2 STRUCTURAL RELIABILITY

4.2.1 Introduction

Structural reliability analyses are beneficial because they provide a rational framework within which the effects in uncertainty and variability can be assessed. The implications of changing variability or uncertainty on the likelihood of a structure performing in a certain way can be ascertained from such analyses.

Background discussion and details of structural reliability and probability-based load criteria are given in a number of sources, for example Ellingwood et al (1980) and ISO 2394 (1998).

4.2.2 The Safety Index

Structural reliability is conveniently measured in terms of probability of failure, where 'failure' refers to the inability of the structure to perform in a certain way. This failure condition is also commonly referred to as a limit state. Depending on the nature of the performance being assessed, failure may refer to any sort of design criteria and may not necessarily mean structural collapse.

The parameters that affect whether or not any given limit state is satisfied can be formulated into a limit state function, the safety margin. If a structural member has a resistance capacity R and is subjected to load demands S, where both R and S are random variables, then the safety margin M is the difference given by $M = R - S$. Failure occurs (in terms of exceeding the resistance R, in whichever way that may be formulated) when the safety margin is less than zero. The probability of failure is then $P_f = P[M \leq 0]$ as shown in Figure 4.1. If R and S are assumed to be normally distributed, then this function can be transformed into a standardised normal probability density function. The safety index, β is then a measure of the number of standard deviations between the mean of the probability density function and the interface between failure and no failure.

Hence, β is a measure of probability of failure, its value increasing with improving structural reliability.

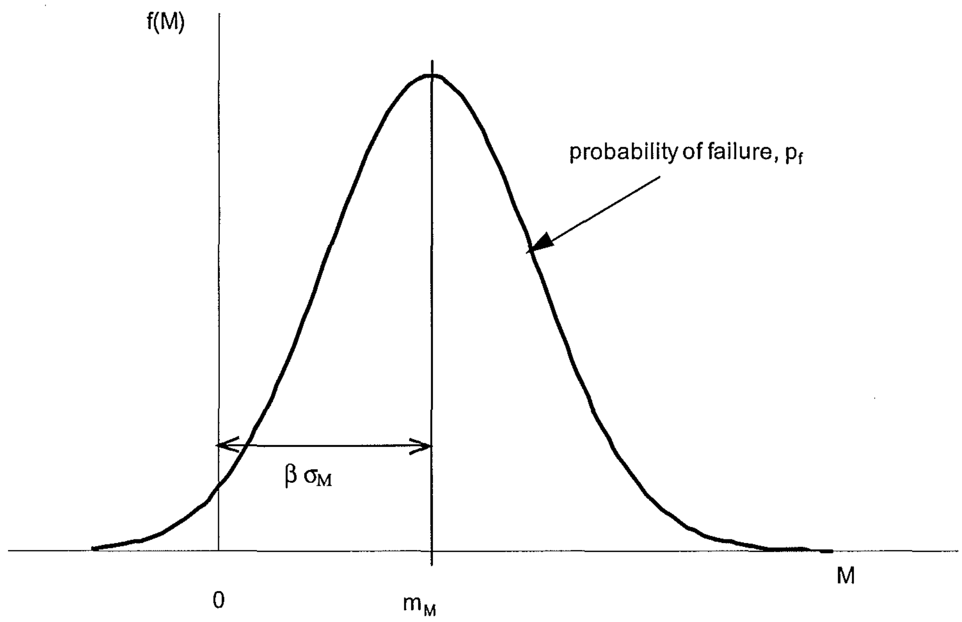


Figure 4.1 Probability density function of the Safety Margin, M

A unit increase in the value of β indicates a decrease in probability of failure by approximately an order of magnitude at low probability levels. Corresponding values of the probability of failure and safety index β are given in Table 4.1.

Table 4.1 Relationship between safety index, β and probability of failure

probability of failure	safety index, β	safety index, β	probability of failure
1.0×10^{-1}	1.28	1.75	4.0×10^{-2}
1.0×10^{-2}	2.33	2.0	2.2×10^{-2}
1.0×10^{-3}	3.09	2.5	6.2×10^{-3}
1.0×10^{-4}	3.72	2.75	3.0×10^{-3}
1.0×10^{-5}	4.26	3.0	1.3×10^{-3}
1.0×10^{-6}	4.75		

4.2.3 Accepted levels of structural reliability

Limit state structural loading codes and materials design codes are calibrated to give as far as possible uniform levels of risk for a wide range of structure types, load combinations. For selected values for load factors and strength reduction factors the actual values for the safety index β vary, depending on the relative magnitude of the loads under consideration. Hence codes are calibrated by selecting target values for the safety index, and the combinations of load factors and strength reduction factors are optimised such that the variation between the actual safety index and the target safety index are minimised.

For steel structures and load combinations of dead load, live load and wind forces, Ellingwood et al, (1980) selected a target value for the safety index $\beta_t = 2.5$. This compares with values for $\beta_t = 3.0$ for load combinations of dead and live loads only and 1.75 for dead and live loads with seismic forces. It can be seen that for the load combinations that include seismic forces, β is 'lower' than for the more 'frequently occurring' external environmental loads. Although the consequences of failure are high for seismic forces, the design forces are also high. Ellingwood et al (1980) regard the lower value for β as an accepted trade-off between high initial construction cost and the cost of failure. However there is also some doubt that this formulation and approach is appropriate for seismic design.

A similar scenario exists for the structural load combinations which include the effects of fire. There is a cost associated with protecting a structure against the effects of fire. For steel structures this is typically the cost of applying passive insulation to shield them from the heat of a fire. If the cost of failure is less than the cost of applying this passive fire protection in the first place then applying the fire protection would not be considered a worthwhile solution.

There do not appear to be any published values suggesting acceptable target values specifically for structural design for the load combination including fire. Target values for the safety index are determined by considering a number of factors, including the safety of designs produced to past codes, the history of failures for different structures and load combinations, relative risk compared with other hazards and a consensus of opinion. The outbreak of fire is not uncommon - certainly more common than the occurrence of wind forces for the ultimate limit state. However, not all fire starts produce conditions which would threaten the strength and stability of a steel structure.

Reinforced concrete buildings are usually not susceptible to the effects of fire to the extent that the structural strength or stability is immediately threatened by the fire at the time that the fire is burning. This is not to say that reinforced concrete structures are immune to fire – the concrete can undergo irreversible chemical/physical changes, the reinforcing steel also loses strength and stiffness when heated, and perhaps most importantly the structures do suffer from the effects of increased strain due to thermal expansion, just like most materials. But the physical size of the concrete members and the thickness of cover concrete that is usually provided for durability and appearance is often sufficient to ensure that a structure will at least survive a fire without major performance problems. Therefore, this issue of structural reliability during fire is more important for steel than for other structural materials.

From the review of methods for determining a target safety index for steel structures, it is suggested that in the absence of a more sophisticated reliability analysis, a value of $\beta_t = 2.5$ is considered reasonable. This is for the case where a structure is being assessed for the combined effects of dead load, live load and fire without regard for whether there is an automatic active suppression system in place. This is the same value of β_t that applies for dead and live loads in conjunction with wind forces.

The probabilities of exceedance that were considered and accepted as the basis for the load effects considered in the New Zealand Code of Practice for General Structural Design and Design Loadings for Buildings (NZS 4203:1992) are outlined in the Commentary to that standard. For load combinations involving gravity loads only (dead and live loads) the accepted exceedance probability for a structure with a nominal 50 year design life is 0.05. Corresponding values for load combinations involving gravity loads and seismic forces (0.10) and for gravity loads and wind forces (0.13) are also given. These correspond to annual exceedance probabilities of 0.0010 (gravity loads), 0.0021 (gravity and seismic) and 0.0027 (gravity and wind).

In the draft Joint Australian/New Zealand Standard Structural design – General Requirements and Design Actions Part 0: General Requirements (DR99309, 1999) the appropriate annual probability of exceedance for structural design actions is stated specifically. For a normal structures, with a design life of up to 50 years, the annual probability of exceedance for design action levels is 0.002, applicable for imposed environmental loads such as those due to wind, earthquake and snow. This value was developed by the Joint Australian/New Zealand committee, in consultation with other APEC countries and with reference to ISO 2394:1998 General Principles on Reliability for Structures. This latter standard was written specifically as a guide for the preparation of national standards covering the design of structures. The assessment of risk underlying the choice of the value 0.002 represents the most recent consideration of the subject, taking into account the risk of failure over the design working life of the structure and also the risk to personal safety of occupants, associated with risk of failure per annum.

It should be noted that structures are designed to withstand load effects with these average exceedance probabilities, without member collapse. Therefore, we cannot simply assume that a steel structure should be designed to withstand the fire conditions that have an annual exceedance probability of less than 0.002 without some knowledge of the performance under these conditions. To be consistent with other load combinations, the members should not suffer collapse when subjected to fire conditions with this exceedance probability.

For non-fire load combinations, the failure condition as evaluated in a probabilistic safety analysis to determine structural reliability is normally based on member performance, not overall structure performance. Hence, the exceedance probability does not necessarily represent the probability of failure of the structure. Reserve strength available from load redistribution means that the actual probability of structure failure is much less than suggested by the target safety index. Similarly, in the evaluation of structural response to extreme fire conditions, the probability of failure of the overall structure will be much less than the annual exceedance probability for the fire conditions, provided failure mechanisms are ductile and involve a certain amount of load redistribution.

It is assumed for the case of fire that the same load factors apply for long term gravity loads, as for other environmental loads such as wind forces, snow loads and seismic forces (Turkstra, 1972 and Turkstra & Madsen, 1980).

A significant difference between a severe fire in a building compared with the effects of wind and seismic forces as ultimate limit state events is that in fire the structure is one of the last items in the firecell to get damaged. With fire temperatures exceeding 550 deg C (an indication of flashover and the limit below which the steel structure is almost certainly going to remain undamaged), all combustible objects in the room or enclosure would be either burning or subjected to very high levels of thermal radiation. Hence the contents would be consumed in whole or part at this stage and almost certainly irreparably damaged. So the relative effect of structural damage is different – there is little point in designing to avoid structural damage in the expectation that this is an important feature of design, if the fire scenario that could damage the structure has already caused significant loss by destroying the contents and affecting continuity of use.

This varies of course, depending on the ratio of the structure cost to the cost of fitout and contents. However, for the fire in an office building in the Broadgate complex in England the cost of repairing severe fire damage to exposed steel structure (51 beams, 5 columns) was less than 5% of the total cost of repair (Lawson, 1991). This is for a building that was not occupied and in use at the time of the fire, so the non-structural damage cost could have been higher. This is consistent with typical cost ratios for repair of fire damaged steel structure known for six other buildings (Dexter and. Lu, 2000).

The exception to this is when the structural element in a firecell also provides support to a substantial part of the structure remote from the fire. The consequential structural damage could be disproportionately high to the extent of the fire or cost of mitigation, which is why the function of each structural element needs to be well understood if it is to be left exposed (without passive fire protection) to a severe fire.

Therefore, in this report a target annual probability of exceedance of 0.002 (2.0×10^{-3}) is selected as a reasonable value for structural design for fire. This is the same value as that used in the draft Australasian Loadings Standard DR99309. It is a slightly lower probability than used in the current (1992) New Zealand Loadings Standard for load combinations involving wind forces (0.0021) and lower than the 0.0062 value corresponding to the safety index $\beta_t = 2.5$ suggested by Ellingwood et al (1980).

4.2.4 Probability of failure and mean recurrence interval

In the remainder of this report, the probability of exceedance may also be referred to in terms of a mean frequency of occurrence, in years (sometimes also referred to as a return period). It is important to understand that this does not mean that an event will happen (at least) once within the stated time frame. It is simply an alternative way of expressing a probability.

For the annual probability of exceedance of 0.002, the corresponding mean recurrence interval is 500 years.

4.3 NEW ZEALAND BUILDING CODE REQUIREMENTS

The New Zealand Building Code objectives and associated mandatory functional requirements and performance criteria are stated in qualitative but not quantitative terms. This is deliberate. Attempting to quantify these criteria and performance objectives is fraught with difficulty because it involves moral and ethical decisions that have a wide impact on the community. However, this leaves designers and certifiers with the difficult task of determining when a design meets the Building Code requirements. In most cases even the prescriptive, non-mandatory deemed-to-comply Acceptable Solutions do not contain sufficient information to enable satisfactory performance to be measured.

For the purpose of establishing compliance with the performance requirements of the New Zealand Building Code, values for exceedance probability for structural loads and for structural reliability that are deemed acceptable to meet other structural performance criteria in the Building Code will also be used as the basis of acceptability for the performance of structure in fire.

5 OCCURRENCE OF FIRES

5.1 FREQUENCY OF FIRE START

5.1.1 Overseas Data

To put into perspective this assessment of risk of inadequate performance of structures in fire it is relevant to consider the frequency of fires in buildings. However, this frequency varies considerably, depending on occupancy type and a range of other factors (age, type of building services, internal finishes, etc.).

In terms of limit state design of structures, the occurrence of fire must be regarded as an ultimate limit state event. Certainly the serviceability limit state is violated, with general loss of amenity of the building, even if only for a short time, and regardless of whether or not performance of the structure contributes to the loss of amenity or is affected by fire. Therefore it is appropriate to consider the frequency of fire start and development into severe fires in the same context as other ultimate limit state events.

Estimates of the frequency of occurrence of fires has been reported in many sources. DD240 (1997) presents data on the 'expected probability of fire starting in various types of occupancy' but in fact this is based on the number of fires reported to the fire brigade. This data, given in Table 5.1, is derived from UK statistics now more than 30 years old. Probabilities (of fire start) are per occupancy.

Table 5.1 Frequency of occurrence of fires reported to fire brigade, per occupancy per year

Occupancy type	probability of fire starts per occupancy per year (average recurrence interval)
Offices	6.2×10^{-3} (160 years)
Assembly, entertainment	1.2×10^{-1} (8 years)
Assembly, non-residential	2.0×10^{-2} (50 years)
Hospitals	3.0×10^{-1} (3 years)
Schools	4.0×10^{-2} (25 years)
Dwellings	3.0×10^{-3} (330 years)

Since not all fires are reported to the fire brigade, this represents only the fires that were either automatically detected or that occupants felt were of sufficient threat to need fire brigade assistance.

The relatively high number of fires in hospitals is not surprising considering that these buildings are typically staffed 24 hours per day, they often have some form of automatic fire detection and the staff are trained to respond by alerting the fire brigade. Hence almost all fire starts will be detected by occupants and reported to the fire brigade. Obviously there is also greater concern for occupant safety than in other occupancies which leads to a more cautious response. In other occupancies, such as offices, the low value more accurately reflects the relatively low frequency of fires.

When one compares the size and activity of the New Zealand Fire Service with that of Civil Defence, it is not surprising to find that the occurrence of fires is more likely than the exceedance probability for other ultimate limit state events for structural design.

Eurofer (1990) lists data for the common building occupancy types relevant to this report, collated from European sources, reproduced in Table 5.2.

Table 5.2 Frequency of occurrence of fires, (per m^2 per year)

Occupancy type	Country/source reference	number of fires per m^2 floor area per year
Offices	United Kingdom	1×10^{-6}
	USA	1×10^{-6}
	France	1×10^{-5}
Dwellings	United Kingdom	2×10^{-6}
	Canada	5×10^{-6}
	Germany	1×10^{-6}
	France	2.5×10^{-4}

Most of the data referenced is relatively old and it is not clear whether the statistics measure all fire starts or, for example, fires reported to the Fire Brigade.

Limited USA data (DD240, 1997) is also available for the probability of fire start per year as a function of floor area (Table 5.3).

Table 5.3 Probability of fire start per year per m^2 floor area

Occupancy type	probability of fire starts per m^2 per year
Offices	1.2×10^{-5}
Public assembly	9.7×10^{-5}

This data suggests that in an office occupancy of 500 m^2 for example, the average recurrence interval for a fire start would be 165 years. Applying this estimate to a building with 10 such office floors, the average recurrence interval for a fire start in the building would be 17 years. For office buildings, these values seem reasonable, although for larger floor areas the suggested frequency is probably pessimistic (more frequent than actual).

According to Thomas et al (1992b) the rate of fire starts in office buildings in the USA is probably 3 to 4 times greater than that for Australia. Using USA data, the estimated rate of fires in the USA is 31 fires per million square metres per year. However, the estimated frequency of fire starts in office buildings in the Sydney CBD is around 8.9 (fire starts) per million square metres per year. For the subject building in the Thomas et al study (34 occupied floors, total office floor area = 56,200 m^2), this suggested a fire start, on average, once every two years. In over 20 years since the building was completed and first occupied there has only been one fire that resulted in fire service attendance.

However, the probability of fire start is not linearly related to floor area (DD240, 1997) which makes it difficult to derive or compare statistics when the areas measured to produce the data are not the same as for the situation in question. The relationship can be expressed in the form

$$P = aA_f^{\,b} \tag{5.1}$$

where

P = annual probability of fire starting

A_f = floor area of the enclosure

a, b = constants related to the specific occupancy type

but values for the constants are only published (DD240, 1997) for industrial occupancies.

A comparison of the various forms of data presented above is therefore questionable, as there are other fundamental differences that remain unresolved, such as the what the data actually records, how it was collected and its validity now 20 or 30 years in the future.

5.1.2 New Zealand Fire Service Data

Statistics collated by the New Zealand Fire Service have been reviewed to assess the frequency of fire starts in New Zealand. Emergency incident statistics for the three years 1992 to 1995 (NZFS, 1996) and the three years 1995/96 to 1997/98 (NZFS, 1999) cover all incidents attended by the Fire Service, but do not include all fires. Fires that start and self-extinguish or that are extinguished by building occupants and not reported to the Fire Service are not included in the statistics.

For the purposes of this report this gap in the data is not important, as the types of fires that occur unreported do not normally pose any threat to the structure. The number of fires that grow unsuppressed to the point where they damage a structure without the Fire Service being aware is likely to be very small.

The total number of structure fires (i.e. fires in structures/buildings) in New Zealand, excluding fires in chimneys, is shown in Table 5.4 for the three years 1995 to 1998. Due to fire-fighter industrial action, some incidents were not recorded in the 1995/96 period.

The proportion of all fires that are structure fires has remained fairly constant over the six years from 1992 to 1998. Total number of fires over this period have increased slightly. Total numbers of fires and structure fires (excluding chimney fires) for the six years 1992 to 1998 are presented in Figure 5.1.

Table 5.4 Total number of structure fires in New Zealand

	1995/96		1996/97		1997/98	
	no. of fires	% [b]	no. of fires	% [b]	no. of fires	% [b]
structure fires [a]	5435	29.8	6294	30.0	6288	25.5
all fires	18242		20951		24664	

Notes:

a. excludes chimney fires

b. % of all fires that are structure fires

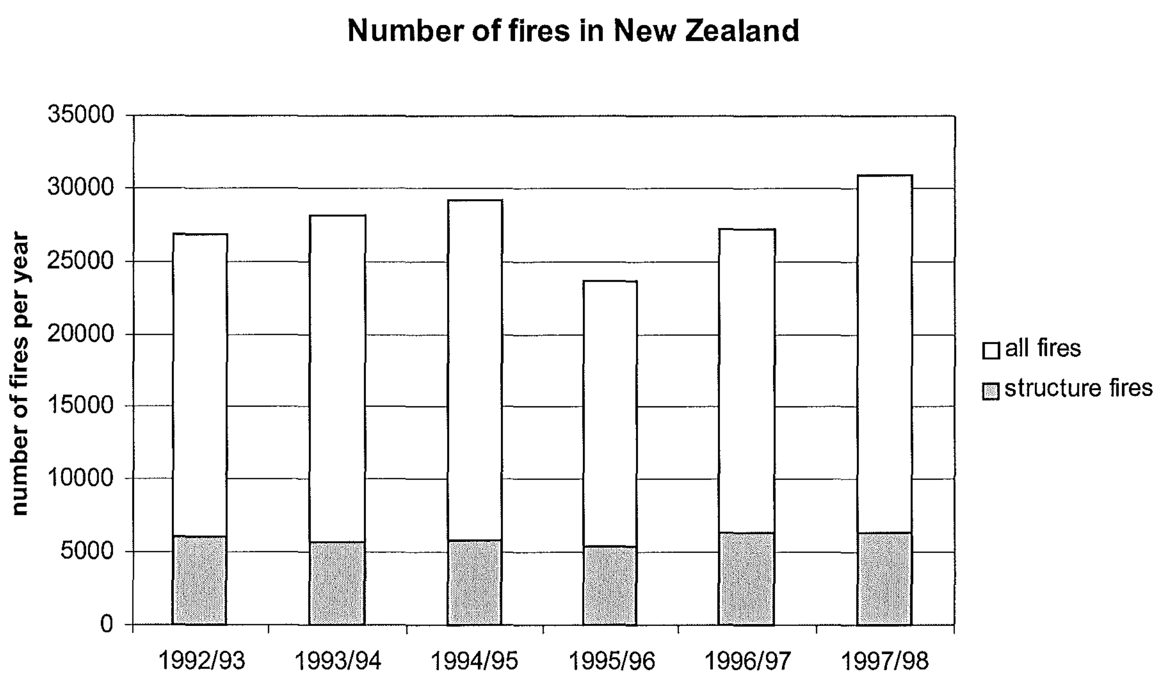


Figure 5.1 Number of fires per year in New Zealand, 1992 to 1998

On average, 28% of fires are structure fires. Using the values for the most recent (1997/98, 6288 fires) period, there is a fire start in a structure in New Zealand (that the Fire Service is aware of) on average 18 times per day.

Of the supposed causes of all fire starts reported (NZFS, 1999), many relate to human error or some form of human involvement. The most common cause of fire start not directly attributable to human behaviour is electrical short circuit or other electrical failure.

Fire Service statistics do not give the specific number of structure fires for various types of occupancy, so some interpretation of the data is required. Residential property is involved in far more fires than other building occupancy types. However, fires may not always involve buildings, evident from the large number of vegetation, car and chimney fires. An adjustment was made to data for residential property reported by NZFS (1999) to correlate with the total number of building fires also reported therein. This is reflected in the estimate of number of structure fires presented in Table 5.5.

Table 5.5 Estimated number of fires in buildings classified by occupancy

Estimate of number of structure fires by occupancy type	1995/96		1996/97		1997/98	
	no. of fires	%	no. of fires	%	no. of fires	%
Public assembly	366	6.7	392	6.2	437	6.9
Education	369	6.8	488	7.8	506	8.0
Healthcare & Detention	202	3.7	264	4.2	262	4.2
Residential (adjusted)	2523	46.4	2748	43.7	2837	45.1
Commercial	821	15.1	1041	16.5	1007	16.0
Primary industry	34	0.6	46	0.7	96	1.5
Manufacturing	660	12.1	721	11.5	597	9.5
Storage	283	5.2	390	6.2	343	5.5
Misc	177	3.3	204	3.2	203	3.2
Totals	5435	100.0	6294	100.0	6288	100.0

It is clear from Table 5.5 that the fires in residential properties account for the highest number of building fires (around 45%). This is partly to be expected – there are more residential buildings than any other type of building in New Zealand. If the number of fires in single houses is deducted from the total number of fires in buildings (but not deducting fires in apartments, flats and other residential buildings) then the number of fires in all of these other buildings amounts to around 4,400 per annum. This reduced frequency corresponds to an average rate of 12 fire starts in New Zealand buildings per day.

For sprinklered buildings, anecdotal evidence shows that a fire of sufficient size to activate sprinklers occurs on average once per week (approx. 50 per year). This information has been obtained from those in the fire protection industry based on recorded incidences of fire start and confirmed independently (C. Mak, pers. comm.; R. Stewart, pers. comm.). Fire Service statistics for 1996 to 1998 (NZFS, 1999) show that on average sprinklers activated at 82 structure fires per year. Fire Service statistics also show for the same period that the Fire Service were called directly on average 52 times per year as a result of sprinkler activation.

This is slightly lower than the average number of fires at which sprinklers activated (82) but could arise because in some cases the fire brigade would have been called by activation of smoke or heat detectors in private fire alarm systems prior to the activation of sprinklers. There are some sprinkler systems not directly connected to fire service monitoring, and some of the fire service records of fires at which sprinklers activated are callouts to systems under construction but not commissioned (hence not directly connected to Fire Service monitoring). This would also account for slightly lower numbers recorded by direct notification to the fire service compared with number of fires in which sprinklers activated.

For this report it is assumed that fires that activate a sprinkler system occur on average 80 times per year (ignoring sprinkler activation in systems not commissioned).

However, this is not a measure of fire starts in sprinklered buildings, as many fires do not develop sufficiently to activate sprinklers, or they are discovered and extinguished before this would occur. The number of fires in sprinklered buildings that were too small to cause sprinkler activation is no longer recorded in the fire service statistics, but for the period 1992 to 1995, there were an average of 115% more fires too small to activate sprinklers than there were that did activate sprinklers (NZFS, 1996). Re-stated, this suggests that of all fires in sprinklered buildings that are recorded by fire service statistics, approximately 55% of fires (recorded by the fire service) are too small to activate sprinklers. This is a gross generalisation for all sprinklered buildings. The proportion of fire starts in any one building or even occupancy type which grow to a size that activates the sprinklers or that are discovered and extinguished before this, depends on characteristics for that particular situation. The duration of occupancy over a 24 hour period, number and type of occupants, presence of other types of automatic fire detectors, degree of compartmentation, etc all play a part in whether or not a fire is discovered in its early growth stages (see discussion on fire spread in section 5.2).

At present, the number of sprinkler systems in New Zealand is approximately 5400. More precisely, this should be regarded as the number of individual sprinkler valvesets. This value is based on a survey of accurate information collected by various parties including AFA Monitoring (who monitor all sprinkler systems with a direct fire brigade connection), Fire Protection Inspection Services (who inspect and approve almost all sprinkler systems on behalf of the Insurance Council of New Zealand), Insurance Council of New Zealand (who are the authority having jurisdiction with respect to approval of sprinkler systems for insurance purposes) and Wormald NZ Ltd (first sprinkler contractor in New Zealand). It is estimated (N. Gravestock, pers. comm.; K. Rothwell, pers. comm.) that around 80% of buildings have only one valveset.

Assuming that the frequency of fire starts derived above from data collected two years ago is accurate now, then the average probability of occurrence of a fire large enough to activate the sprinkler system in a sprinklered building in New Zealand is estimated to be 80/5400 = 0.015 per year (average recurrence interval 67 years).

Similarly, the average probability of occurrence of a fire start in a sprinklered building in New Zealand, including those fires too small to activate the sprinkler system, is estimated to be 178/5400 = 0.033 per year (average recurrence interval 30 years). However, this is a very generalised statistic and may not apply to all building or occupancy types.

These values are of the same order of magnitude as those derived from international data (see Table 5.1 above) but an accurate comparison is difficult. The expectation that the frequency of fire starts should necessarily be similar from country to country is also questionable.

For risk assessment carried out as part of this research the probabilities assessed from New Zealand data have been used.

5.2 LIKELIHOOD OF FIRE SPREAD

5.2.1 Overseas Data

Not all fire starts develop into growing fires, not all growing fires develop to reach flashover and not all fires that reach flashover are of a severity or duration that threaten the stability of a steel structure. (However in this report, because of the difficulty in accurately assessing when a fire would threaten a steel structure, it is assumed that all fires that reach flashover are capable of threatening structural stability).

DD240 (1997) lists the proportion of fires that spread beyond the room of fire origin, for single storey and multi-storey buildings (Table 5.6):

Table 5.6 Proportion of fires that spread beyond the room of fire origin

Occupancy type	Proportion spreading	
single storey buildings	day	night
Assembly	0.19	0.44
Shops	0.10	0.18
multi-storey buildings		
Assembly	0.13	0.25
Shops	0.13	0.16
Residential	0.10	0.19
Offices	0.08	0.21
flats, maisonettes	0.10	0.15

The likelihood of fire spread beyond the enclosure of fire origin is dependent on a wide range of variables (FCRC, 1996), including:

- location of the fire start

- quantity, distribution and combustibility of fuel load in the building
- ventilation available to the enclosure of fire origin
- presence of an automatic fire suppression system
- location and effectiveness of fire separations
- presence of an automatic fire detection system
- distribution of occupants in the building
- whether a building is occupied 24 hours or only during the day
- the time of fire start (day or night)
- presence and visibility of first-aid fire-fighting equipment and occupant familiarity and willingness to use it

If an automatic suppression system is present and operating it is likely to do so before the fire reaches flashover and to control fire growth (at least to the extent of limiting spread beyond the room of fire origin). If occupants or the fire brigade are present and are able to attempt fire-fighting, this is also likely to be effective only if it is carried out before the fire reaches flashover. Even with protective clothing, the ability of the fire service to reach a fire in time and then apply water to control fire spread beyond the room of origin is limited if the fire has reached flashover in that room. Therefore, it is reasonable to assume that if a fire reaches flashover it can and will spread beyond the room of fire origin, unless that room is a firecell in itself (bounded by effective fire-rated construction). Hence, the probability of a fire reaching flashover is related to the likelihood of it spreading from the room of fire origin. A fire may reach flashover and be contained to the room of fire origin (by fire rated construction or by fire-fighting), but this is only likely to occur if the room size, and hence fire size, is relatively small.

If we are interested in estimating the proportion of fires that progress beyond the room of origin without occupant intervention, the statistics for offices and possibly also assembly areas are likely to be more representative because these buildings are not occupied overnight. For these two occupancies the average proportion of fires spreading beyond the room of origin is 0.23. For the other occupancies, where there would be a greater extent of occupant intervention, the average value for night fires is 0.17.

Therefore it is reasonable to suggest that that the proportion of fires reaching a size that could begin to threaten the stability of a member in a steel structure can be estimated from the data for the proportion of fires that spread beyond the room of fire origin. For buildings within the scope of this report (see section 1.3 herein), this may be assessed conservatively as 0.25. For buildings that are occupied overnight, hence there is a greater chance of occupant intervention, a lesser value of say 0.20 could be used.

Of course, this estimate is fairly crude. The data may or may not include sprinklered buildings so the proportion may not indicate the likelihood of a fire to grow to reach flashover in the absence of sprinklers.

In comparison, DD240 (1997) also suggests that, on average approximately 10% of all reported fires grow to a size and severity to cause significant structural damage. Considering that the data relates more to buildings with automatic alerting and direct alarm connections and hence a significant proportion (assume say up to 50%) of the reported fires will be in sprinklered buildings, the real value for fires not controlled by a sprinkler system might be about double this value i.e. 0.2. This is consistent with the other estimate based on data in Table 5.6.

Harmathy (1989) reviewed data collated in the FEMA/USFA (USA) National Fire Incident Reporting System (NFIRS) database to evaluate an optimum balance between cost and benefit of fire protection measures. His interpretation of fire spread data indicated that 79% of fires would not reach flashover and would not spread beyond the room of origin. A further 6% of fires would reach flashover but would not spread beyond the room of origin and the remaining 15% would reach flashover and would spread beyond the room of origin. This data applies to fires in buildings that are not equipped with sprinklers.

Thomas et al (1992b) assumed that the probability of a fire developing into a 'partial-flashover type fire' given that ignition had occurred is 0.2, (assuming no fire service intervention).

5.2.2 New Zealand Data

An indication of the proportion of fires that spread beyond the enclosure of fire origin, or from the item first ignited was also obtained from reviewing New Zealand Fire Service statistics (NZFS, 1999). These values include fires in which there was fire service intervention, so the statistics derived reflect actual fire behaviour.

In structure fires, the fire service statistics record 'structural damage' – smoke, water and flame damage to the fabric of the building/structure – classifying the extent to which this is confined –

- to the object of origin
- to part of room or area of origin
- to room of origin
- to firecell of origin
- to floor of origin
- to structure of origin,

or whether the fire spreads beyond the structure of origin. Flame damage is assessed as evidence of direct burning to floors, walls or ceiling. To assess the number of fires that did not grow large enough to begin to threaten the stability of the structure, all fires in which 'flame damage did not extend beyond part of the room' were counted. These represent fires which did not spread and did not reach flashover in the room of fire origin. Therefore they were unlikely to have produced sufficient heat output or burnt for long enough to threaten structural performance. There would also be many fires that produced damage by direct burning beyond part of the room (of origin) without necessarily producing fire conditions that affect structural performance, so this underestimates the number of fires which did not threaten structural performance.

All other fires reported to incur structural damage (in which flame damage extended beyond part of room) were conservatively regarded in this research as having spread and grown to a size capable of threatening structural performance. These amount to around 30% of all structure fires (excluding chimney fires). This data is summarised in Table 5.7.

Table 5.7 Fire spread in structure fires derived from NZFS statistics

	1995/96		1996/97		1997/98	
	no. of fires	%	no. of fires	%	no. of fires	%
1. total no. of structure fires	5435		6294		6288	
2. structural damage fires	2793	51 [a]	2796	44 [a]	2679	43 [a]
3. structure fires in which flame damage did not extend beyond part of room	1054	38 [b]	1012	36 [b]	902	34 [b]
4. structure fires in which flame damage not confined to part of room	1739	32 [c]	1784	28 [c]	1777	28 [c]
5. % of all structure fires that were not extinguished		16		13		16
Mean value (of 4 & 5) % of structure fires assumed to spread and reach flashover)		24		21		22

Notes:

a. % of all structure fires which incurred 'structural damage' as classified by NZFS (i.e. damage to building fabric)

b. % of 'structural damage' fires

c. % of all structure fires

This suggests that in only 30% or less of structure fires is there potential for fire spread and damage to structure, because flame damage was not confined to part of the room of fire origin. However, the fact that the flame damage spread beyond part of a room is not a strong indicator that the structure was affected. Fire Service statistics also record the number of structure fires that were not extinguished.

It is reasonable to assume that in all such fires the structural performance was or could have been adversely affected. But the converse is not true. The mere fact that the fire was extinguished is not an assurance that the structure was not affected. So the true proportion of fire starts expected to spread beyond the object of initial burning, grow to flashover and affect structural performance is between these two values: more than the proportion of fires not extinguished but less than the proportion that incur flame damage beyond the part of room or area of fire origin.

In this report, the mean of these two values is assumed to be a reasonable value for the proportion of fires that grow, spread beyond the object of initial involvement and in which adverse structural performance could be expected. This is taken as 0.20. Obviously, this value takes into account fire service intervention. This value is also consistent with estimates based on international data. This value applies to all fires reported to the fire service, not just those fires that are large enough to activate sprinklers.

6 SPRINKLER RELIABILITY AND EFFICACY

6.1 INTRODUCTION

The effectiveness of sprinklers to perform as intended (to at least control and hopefully suppress a growing fire) is dependent on many factors. These can be categorised in terms of reliability and efficacy (Bennetts et al, 1998).

Reliability is a measure of the system to operate when required and in the way in which it was designed (for example, to activate and then deliver water in the protected area). Reliability can be measured in probabilistic terms on a scale from 0 (unreliable) to 1 (always operates when required).

Efficacy is a measure of the system achieving a desired objective, given that it operates. This can also be measured in probabilistic terms on a scale of 0 (never achieving the desired objective even though it operates) to 1 (always achieving its desired objective).

Reliability can be measured in absolute terms, but efficacy can only be measured in terms of stated objectives. Effectiveness is the product of reliability and efficacy and is therefore also a function of the objective. In this way, sprinkler systems with the same reliability will have a different effectiveness, depending on the objective. This is why the results of this study, which are concerned with sprinkler effectiveness relating to performance of steel structures in fire, are not directly applicable to a fire scenario with a different objective (e.g. life safety in a high rise building).

This also explains why there are differing opinions on the effectiveness of sprinklers to achieve a certain performance (Allen, 1999a, 1999b; Schulte 1999a, 1999b). Reliability is confused with effectiveness. A system can have high reliability with low efficacy depending on the objective.

In this report, the desired objective for sprinkler operation is control of a fire to the extent that the stability of a steel structure is not threatened. This is probably one of the least demanding objectives for sprinkler system operation because it is not directly concerned with suppressing a fire, or the controlling a fire to a certain maximum size for smoke control, or even preventing the fire from spreading within the room of fire origin. The only concern is that the sprinkler operation controls the fire to the extent that it does continue to grow and that the temperatures produced in the fire do not affect structural stability.

The performance of steel structures in fire is discussed in detail in section 9 in this report. Until fire upper layer temperatures approach around 550°C a steel structure is not likely to be affected. It is relatively easy to extract data from reports of sprinkler activation that confirm whether or not sprinklers would have been effective in controlling fire temperatures below this value. If fire temperatures exceed this value it is likely that the fire has reached flashover and the sprinklers will have been overwhelmed by the fire.

Examining sprinkler efficacy and reliability can be done in different ways and in varying degrees of detail. For the refurbishment study of the office building at 140 William St, Melbourne, Thomas et al (1992a, 1992b) researched the problem in considerable detail, looking at the operation and reliability of a wide range of sprinkler system components. This approach is analytical and predictive, assessing the reliabilities of the components, the probability of various events occurring (including the outbreak and development of fire) and combining these in a form which determines the overall probability of occurrence of an event. This risk analysis can be described using an event tree.

Conversely, the data collated by Marryatt (1988) looks at the results of fires in sprinkler protected buildings, concentrating on the effectiveness of sprinkler activation but without particular concern for the reliability of individual components. This method, which reviews actual performance of the systems does not suffer from the problems of predicting reliability based on incomplete data, but at the same time the validity of the data depends on having a comprehensive and representative sample. The probability of failure of the overall system is the main outcome of this latter study. However, in Marryatt's case the data relates to a conditional probability – the effectiveness of sprinklers given that a fire occurs.

To measure sprinkler effectiveness in terms which are useful for assessing structural reliability, it is necessary to quantify the annual probability of the sprinklers not controlling a fire to a level that does not threaten a structural steel frame.

6.2 STATISTICS FOR SPRINKLER EFFECTIVENESS

Various sources have published values for the expected probability of successful sprinkler operation. Some of these are intended to be used in a probabilistic risk assessment for fire safety. Other data is based on a study of general sprinkler reliability or is obtained from studies of specific buildings.

For example, DD240 (1997) suggests the "probability of [sprinkler] fire protection systems failing to operate as designed" as 0.05 (effectiveness of 0.95). Surprisingly this data appears to originate from a study in Australia, which may indicate that the statistic is relevant for sprinkler systems in Australia (and New Zealand) but may not be relevant for the United Kingdom, for the reasons discussed in section 6.3 herein.

The "probability of fires getting out of control" in a building with a sprinkler system is 0.02 (effectiveness of 0.98) according to Eurofer (1990). It is not clear from this reference what is meant by this and how it correlates to the study reported herein. This could refer to a fire that reaches flashover or to a fire that can no longer be contained by the fire service within a firecell (floor or building), hence is 'out of control'.

The probability of successful sprinkler activation in a fire that is capable of reaching flashover is given as 0.99 in the Australian Fire Engineering Guidelines (FCRC, 1996) i.e. probability of failure of 0.01.

It seems intuitively correct that the combination of a sprinkler system in conjunction with the availability of a responsive fire service should reduce the probability of a structure being exposed to a fire which threatens its stability. The hydraulic part of a sprinkler system is inherently very reliable, so components that are most likely to reduce the likelihood of sprinklers controlling a fire are: water supply (town main or reservoir pressure/flowrate/availability), pumps and valves. On arrival at a fire (in response to the direct notification from sprinkler activation) the fire brigade can supplement water pressure or flowrate and open valves. Hence about the only fault that can remain is a blockage in the sprinkler pipework or complete failure of the town main to supply any water in all streets around a building. As both of these events are very unlikely, it is almost certain that the fire brigade can successfully boost a sprinkler system as required. Given that the initial activation of the sprinklers will offer at least some benefit in the form of initial fire control or wetting of fuel items in the vicinity of the fire, which in turn will slow fire growth, arguably the fire brigade are more likely to be able to control a fire when they arrive, either to stop it spreading within or beyond a firecell, or to reduce its effect on the building structure, if a sprinkler system has been installed.

However, because the effect of fire brigade activities are not amenable to calculation, the effect of these is very difficult to quantify. Eurofer (1990) note that the "probability of fires getting out of control" reduces from 0.02 with 'sprinklers only' down to 0.0001 where both sprinklers and an effective fire brigade are available. It is not clear what sort of fire outcome this refers to – e.g. a fire that reaches flashover or perhaps is confined to one firecell – and whether this is an annual or design life exceedance probability.

Although not a direct function of sprinkler reliability, fire brigade availability does have an effect on the probability that a structure will be exposed to a fire that threatens its stability.

6.3 STUDY BY MARRYATT

6.3.1 Introduction

One of the most comprehensive studies on sprinkler effectiveness in New Zealand and Australia was conducted by H.W. Marryatt. Two studies were published (Marryatt, 1971, 1988) of which the second is the most comprehensive and is the main one referred to in this report. This study reviewed aspects of water supply reliability as well as issues relating specifically to sprinkler system design and construction.

Statistical data reported in Marryatt's study (1988) of the performance of automatic sprinkler systems is based on a review of 9022 fires in Australia and New Zealand for which detailed fire reports were available, for the 100 years from 1886 to 1986. Data available on the performance of sprinklers since 1986 has also been reviewed in this study.

Marryatt classified sprinkler performance in terms of 'fires controlled' and 'fires not controlled'. 'Fires controlled' refers to fires which have either been completely extinguished or controlled by the automatic sprinkler system to the point that they would be extinguished even if supplementary action had not been taken by the fire brigade or others. 'Fires not controlled' are those in which automatic sprinkler systems have been unable to prevent major damage to the building and its contents. These are in effect the objectives by which sprinkler efficacy, hence effectiveness, has been measured.

For the scope of this report, which is interested in the effect of fire on steel structures, these classifications are not ideal. Leaving aside for the moment the particular case of direct flame impingement from a fully developed fire involving an isolated fire source such as a car fire, steel structure stability is almost never threatened if the (upper layer) fire temperatures in an enclosure does not reach more than around 550°C. It is reasonable to assume that all fires classified by Marryatt as 'controlled' would not have had fire temperatures as high as this, or at least not for any significant length of time, because sprinklers would have activated and begun to control the fire at temperatures much lower than this. Also, this temperature represents conditions approaching flashover at which point the fire is usually accompanied by pyrolysis of a significant proportion of the contents and is much more likely to overwhelm the sprinkler system.

Therefore, it is also possible that some of the fires classified as 'fires not controlled' would not have threatened structural stability, even though there may have been significant damage to the building contents. At a fire scene the demarcation becomes subjective. Hence it is assumed for the purposes of this report that in fires classified as 'controlled' the performance of the structure would comply with New Zealand Building Code requirements. It is also assumed that fires classified as 'not controlled' would have been sufficiently severe to be capable of affecting steel structure performance to the extent of non-compliance with (current) Building Code requirements. This latter assumption is conservative because it overestimates the number of fires that would have had an adverse effect on structural performance.

In this section of the report, the term 'uncontrolled' is used to refer to 'fires not controlled' as classified by Marryatt, when applied to fires in sprinklered buildings.

6.3.2 Scope of Marryatt's data

It is believed that the records on which Marryatt's studies were based are close to 100% complete: 98% of fires in sprinklered buildings that activated the sprinkler system in the period 1886 to 1968 were reviewed and 94% of the same type of fire in the period 1968 to 1986 (C. Mak, pers. comm.). All fires in sprinklered buildings that were not controlled by the sprinkler system have been included for the 100 year period. There were 289 fires listed in Fire Brigade records in which the sprinkler systems operated satisfactorily but for which detailed reports were not available. Hence the statistics calculated for sprinkler effectiveness underestimate the proportion of successful activations.

It is important to understand exactly what the data collated by Marryatt actually represents to confirm its applicability to the subject of this research. Although the records cover 100 years and are understood to be close to 100% complete, the data is only a part of a statistical population. For example, the study does not include data on sprinkler performance any time after 1986. Obviously it is useful and important to know how representative this sample is of the population, as this determines the accuracy of extrapolations made to predict the future performance of sprinkler systems.

The statistics do not record all fires, nor do they record data for fires in all sprinklered buildings – only those that activated the sprinkler system. Because the statistics do not record all fires, the occurrence of fires in unsprinklered buildings is not included, so the data cannot be directly used to estimate the general probability of a fire occurring. A number of fires would have occurred in both sprinklered and unsprinklered buildings that did not activate the sprinkler system.

The statistics measure the effectiveness of automatic sprinklers to control a fire, in cases where a fire in a sprinklered building has activated the sprinkler system – a combination of two events. That is, the data measures the occurrence of both a fire that activated the sprinkler system, and the effectiveness of sprinklers to extinguish and/or control the fire, together with the number of sprinkler heads that activated. The statistics derived are therefore conditional.

Hence, Marryatt's data measures the proportion of fires in sprinklered buildings that are successfully controlled by sprinklers but does not directly provide a probability of occurrence (of a fire that activate sprinklers in sprinklered buildings) because there is no data provided on the total number of buildings or sprinkler systems in each year for which data was collected. If the sample size and population size remained constant then arguably this would not matter: the statistics collected for the 100 years of the study could be applicable today and in the future. But the number of sprinklered buildings is increasing, both in absolute terms and relative to the total number of buildings. During the 100 year period that data was collected, the number and proportion of sprinklered and unsprinklered buildings has changed. This is also true for specific occupancy types. So although the effectiveness of sprinklers to control fires as a proportion of sprinkler activations is known, the changes to the characteristics of the statistical population need to be incorporated. This could alter both the number of sprinkler activations and rate of effective sprinkler activations. Changes which are more difficult to measure are occupancy type or fire load energy density of fuel for different occupancies.

Hence for a new building with a given occupancy type being assessed today (to predict future performance), Marryatt's data does not provide enough information to make an assessment of the probability of occurrence of a fire in a building reaching a size that could activate the sprinkler system. To do this, data on fire starts (NZFS, 1999) has been analysed in order to estimate probabilities of occurrence and variations over time. A discussion of this analysis is presented in section 5.1 herein.

It has also been assumed, for the purposes of assessing future occurrence of fire, that all of the fires reported by Marryatt were of a size and severity that could activate the sprinkler system. This is a reasonable assumption, given that in all fires in Marryatt's study the sprinkler system was activated. Occurrences of sprinkler activation that were not a direct result of the fire are assumed to be so few as to be insignificant. It is conservative to ignore these as doing so increases the assessed probability of fire occurrence.

Marryatt's data can be used to calculate the effectiveness of sprinklers when a fire occurs but it does not measure absolute sprinkler reliability. The proportion of sprinkler systems that will operate on demand at any given time is less than that given by Marryatt's data because sprinkler reliability is not recorded in situations where a fire did not occur. However, as long as there is not a fire at the same time that a sprinkler system is not able to operate then there is no adverse effect on the performance of the structure. Also, one of the important attributes of sprinkler systems in New Zealand is that they are monitored (see section 6.4 herein). This means that the systems are unlikely to be left inoperative for very long so their point-in-time reliability is high. Hence the combined probability of the sprinklers not being operative at the same time as the infrequent occurrence of fire start is very low (very high sprinkler reliability).

6.3.3 Interpretation of Marryatt's data on sprinkler performance

The key results from the study by Marryatt (1988) for the occupancies relevant to this study of structural performance are summarised in Table 6.1.

Table 6.1 Summary of performance of automatic sprinklers in fires for selected occupancies which activated the sprinkler system, 1886 to 1986, Australia and New Zealand

Occupancy [a]	number of fires in 100 years	number of fires not controlled in 100 years [b]	max number of sprinkler heads activated
Residential (including hotels, motels)	163	0	6
Public assembly (including bowling alleys, restaurants, grandstands, terminals)	90	2 (1)	5
Educational	26	0	4
Institutional (healthcare and detention, including prisons)	200	0	5
Office	383	0	>10
Retail (including department stores, shops, supermarkets)	1186	5 (2)	>10
Other - car service stations, garages, showrooms, including garages part of major occupancy	96	0	>10
totals	2144	7	

Notes.

a. Occupancies which are excluded from this study are those with highly variable fire loads and high sprinkler hazard categories such as storage, warehouse, manufacturing, typically found only in single level buildings.

b. Values in brackets are the number of fires from the 82 years of the first survey (Marryatt, 1971) and which are already included in the first value given in this column

For the occupancies selected for this report (refer section 0 herein), the average proportion of uncontrolled fires is $7/2144 = 3.3 \times 10^{-3}$ (0.33%). For the fires in all occupancies presented in Marryatt's study, the average proportion of uncontrolled fires is higher than this:

$49/9022 = 5.4 \times 10^{-3}$. This is not surprising, as the occupancies selected for the scope of this report are those with lower likelihood of sprinkler failure for that very reason – to take into account this better than average sprinkler performance.

Restated, for the occupancies that are included in the scope of this report, of the fires that occurred in sprinklered buildings (in the period 1886 to 1986) that were large enough to activate the sprinkler system, the fire was 'controlled' by the sprinklers in 99.67% of the cases. This can be considered to be a measure of sprinkler effectiveness but is not a probability of occurrence in absolute terms. However, it can be used to derive a conditional probability: if fire occurs in a sprinklered building that is large enough to activate the sprinkler system then the probability that it will be controlled by the sprinkler system is 0.9967.

However, to ignore the cases of uncontrolled fires in other occupancies is misleading. It is important to review the principal causes for all fires that were not controlled by the sprinkler system as this has a significant effect on the interpretation placed on the reliability of sprinklers and the failure to control an outbreak of fire. In some cases, the sprinkler 'failures' may not be related to the occupancy involved and could be common to potential failures in other occupancy types.

Marryatt identified eight factors which contributed to the 49 fires not being controlled by sprinklers.

1. severe fires which started external to the sprinklered building
2. either sprinkler protection not extended into concealed spaces or lack of sub-division of voids with fire-stopping barriers
3. explosions which damaged the sprinkler system to the extent that fires following the explosion could not be controlled
4. excessive stacking height or storage of high hazard materials
5. ignition of solvent vapour or flammable liquids
6. sprinkler valve shut off for maintenance

7. water supplies shut off and alarms disconnected by arsonists before setting fire to buildings

8. inadequate water supply (either inadequate pressure or power supply to electrical pumps turned off during fire-fighting)

Of the 49 fires classified as 'not controlled' by the sprinkler system, 15 fires involved large numbers of sprinklers operating and it was clear that control of the fire would not have been achieved if the fire brigade had not intervened. However, given the extent of fire as measured by the large number of heads that operated, without the sprinkler system the fire is unlikely to have been controlled to the extent that the fire service were able to extinguish the fire. In these fires the buildings and most of the contents were saved. Although fire brigade actions played a significant role, the performance of the sprinkler system was responsible for the satisfactory performance of the building structure in all fires. All of these fires occurred in occupancies that are outside the scope specified for this report. Ten fires involved storage of goods of above average fire hazard. Therefore in this report only **5** of these 15 cases are regarded as fires not controlled by the sprinkler system, within the scope of this report.

Of the remaining 34 fires, 27 occurred in occupancies that are outside the scope of this report.

Two cases involved arson, in which the perpetrators deliberately shut off the main sprinkler stop valve and disconnected the fire alarms before setting fire to the buildings. These are not regarded as failures of the sprinkler system to control a fire, but highlight the need for monitoring of main stop valves. With direct monitoring of systems, as provided in New Zealand, this type of failure is unlikely to occur because the fire brigade would be called as soon as the system was tampered with.

Two cases involved the premature shut down of the main sprinkler valve by fire-fighting personnel, thinking that the fire had been extinguished. The fire re-established itself and overwhelmed the sprinkler system. Arguably these are not cases of inadequate sprinkler system performance but they have been included as they highlight a potential problem that can occur.

As far as sprinkler operation was concerned, the reasons for the uncontrolled fire are not applicable to the occupancies covered by this report in 18 of the 34 cases. Therefore, for the purposes of this report and its assessment of sprinklers on performance of steel structures in fire, only **16** of these 34 fires are regarded as examples of fires not controlled by the sprinkler system.

Of the 49 fires classified as uncontrolled by Marryatt, for the purposes of this report 16+5 = 21 fires are regarded as cases where the sprinkler system did not perform satisfactorily. Of these 21 fires, 19 occurred in Australia and 2 occurred in New Zealand over the 100 year period of the study.

Apart from one case where the sprinkler system was shut down and undergoing maintenance at the time of the fire, none of the other 48 cases occurred due to a lack of inherent sprinkler system reliability.

The three cases of uncontrolled fires in sprinklered buildings in New Zealand reported by Marryatt (1988) all occurred prior to 1968. This gives an average annual rate of occurrence of approximately $3 \div 82 = 0.0036$.

More recent data compiled by Wormald NZ (C. Mak, pers. comm.) confirms that the average rate of fires in sprinklered buildings in New Zealand still applies. For all sprinklered buildings (all occupancies) there have been 4 uncontrolled fires in New Zealand for the period December 1886 to April 2000 (113 years) out of an estimated total of 2,051 fires. This number of uncontrolled fires is known to include all such fires in New Zealand, but the number of fires in sprinklered buildings is based on the number of fires in buildings known to Wormald. Therefore this underestimates the sprinkler effectiveness. Nevertheless, the sprinkler effectiveness based on this data is at least 99.80%.

This fourth case (occurred after 1986) changes this average annual rate of occurrence to $4 \div 113 = 0.0035$ (uncontrolled fires in sprinklered buildings in New Zealand per year) – an average recurrence interval of 28 years. This fourth case was also the result of over-height storage in a warehouse-type occupancy. Hence, for this report the probability of uncontrolled fires occurring in sprinklered buildings in New Zealand containing the occupancy types referred to in the scope, is based on a history of occurrences of two fires in 113 years (1886 to 2000).

It is important to note that the sample sizes for some occupancies are still very small. This can distort the true risk associated with these occupancies. For example, there are five occupancy classifications for which no uncontrolled fires were recorded over the 100 years. This does not mean that the sprinkler systems in these buildings are perfect but is a result of both the small sample size and low frequency of occurrence. There is a finite probability that an uncontrolled fire will overwhelm sprinklers in one of these tenancies and this could happen tomorrow. We do not know what that probability is, but it would be conservative to assume that the average proportion of fires that are uncontrolled (3.3×10^{-3}) also applies to these occupancies for which there have been no recorded failures, because if the true value was higher than average we could expect to see evidence of this in the statistics collated over a 100 year period.

Other shortcomings in the data must be recognised when applying results to particular occupancies. The classification of occupancies by Marryatt is not necessarily the same as interpreted today for estimating the risk to a future buildings, particularly in buildings where there are a number of uses. Also, because the frequencies and sample size of fires in some occupancies are low, the occurrence of one fire can significantly change the apparent performance. For example, the occurrence of one uncontrolled fire in a residential building one year after the end of the reporting period changes the proportion of uncontrolled fires for this occupancy from an assumed average value of 3.3×10^{-3} to $1/163 = 6.1 \times 10^{-3}$, which is nearly twice the average. Similarly, a single fire not controlled by a sprinkler system that occurs in one type of occupancy, may occur for reasons not associated with the occupancy type. General trends based on larger sample sizes are needed to confirm apparent differential risks by occupancy.

The reasons why the uncontrolled fires occurred need to be more closely examined to see if they were particular to that occupancy. Because of the small number of uncontrolled fires, the variation in proportion of fires controlled for particular occupancy types could be just that: a variation in the statistics of the small sample size, but not necessarily indicative of a trend.

It is also important to note that the classifications of occupancy type as given by Marryatt do not necessarily align with Purpose Group classifications given in the BIA Fire Safety Documents (BIA, 1995) or descriptions of classified uses given in the Building Act (New Zealand Govt, 1992). In particular, because Purpose Group classifications are general and can apply to a wide range of occupancies, it is important not to assume that it is appropriate to extrapolate data for a particular occupancy type (as given by Marryatt) to a particular Purpose Group defined in the BIA Acceptable Solutions.

It is also unfortunate that the occupancy classifications are not well-aligned with the property classifications used by the New Zealand Fire Service in their emergency incident statistics (NZFS, 1999) so that statistics can be combined with more confidence.

Despite any concerns related to occupancy types, the time frame covered by this sample is long – 100 years – which is twice as long as the nominal 50 year design life which forms the basis of the accepted probability of failure (discussed in section 4.2.3 herein). In addition, the sample covers almost 100% of fires in sprinklered buildings in Australia and New Zealand over this period. This improves the confidence with which the average sprinkler reliability results can be applied. Marryatt's detailed analysis by occupancy indicates that the variation between the average value and the worst case is less than an order of magnitude.

The conditional probability of sprinkler effectiveness outlined above is significant, but in itself is not directly applicable to an assessment of structural reliability. Table 6.1 shows that for the occupancies listed, 7 fires occurred over the 100 year period which were not controlled by the sprinkler system. This gives an average rate of occurrence of 0.07 per year of fires in sprinklered buildings in both Australia and New Zealand that were not controlled by the sprinkler system over this period. Without knowing the number of buildings or occupancies in any given year it is difficult to calculate a precise a rate of occurrence on a per building or per occupancy basis. Marryatt does not report the total number of sprinklered buildings that existed in each year of the study or as an average over the 100 years – this data was simply not available.

Given the very few cases of uncontrolled fires in sprinklered buildings it is difficult to establish whether the rate of occurrence is greater now than in earlier decades. In fact there is evidence to suggest that modern sprinkler installations could be more reliable than older systems, if the timing of uncontrolled fires is any indication. Nevertheless, the average annual rate of occurrence assessed above underestimates the rate applicable to the most recent years in the sample, when the total number of buildings, number of sprinklered buildings, number of fires and hence annual rate of occurrence are all higher than the average for the 100 year period. For example, the average number of fires per year (in sprinklered buildings) analysed by Marryatt increased from 70 in the period 1886 – 1968 to 183 in the period 1968 – 1986. The average number per year in this latter 18 years was more than twice the average calculated over the 100 year period (90 fires per year). Hence the average rate of occurrence that might apply to current and future sprinklered buildings could be up to around 0.14 (uncontrolled fires in sprinklered buildings) per year.

This value applies to both Australia and New Zealand. For reasons given in section 6.4, it is appropriate to consider the results for each country independently. The values for New Zealand are of most relevance to this report.

Of the 9022 fires analysed by Marryatt up to 1986, 5591 of these were recorded by Wormald Australia, 1511 were recorded by Wormald New Zealand, with the remaining 1920 of unspecified origin (C. Mak, pers. comm.).

Marryatt's data provides an average rate of occurrence of an uncontrolled fire in a sprinklered building. In order to calculate the probability of this occurring in any given sprinklered building in Australia and New Zealand, the total number of sprinklered buildings is needed (i.e. the population of the set).

In 15 (30%) of the 49 fires not controlled in the 100 year period of the study that are relevant to this report, Marryatt noted there was no damage to the building structure and there were no cases in any of the 49 fires of distortion to structural steel members. This demonstrates desirable performance from the steel structure, but could also be attributed to early on-site presence of the fire service (in response to direct notification from the sprinkler system). However, this outcome could still be regarded as a beneficial attribute of having sprinklers installed if the building is located within a reasonably short response time from the fire service.

6.3.4 Statistics for suppression and extinguishment of fires

The data compiled by Marryatt relates not only to the effectiveness of sprinklers in controlling fires but also records fire brigade attendance and occupant intervention in suppressing fires. As discussed in section 6.4.1 herein, the direct connection to fire service monitoring and their quick response to fires which result in sprinkler activation has had an important influence on controlling fires in sprinklered buildings. The method of suppression that was applied for fires (in sprinklered buildings) that were effectively extinguished is shown in Figure 6.1.

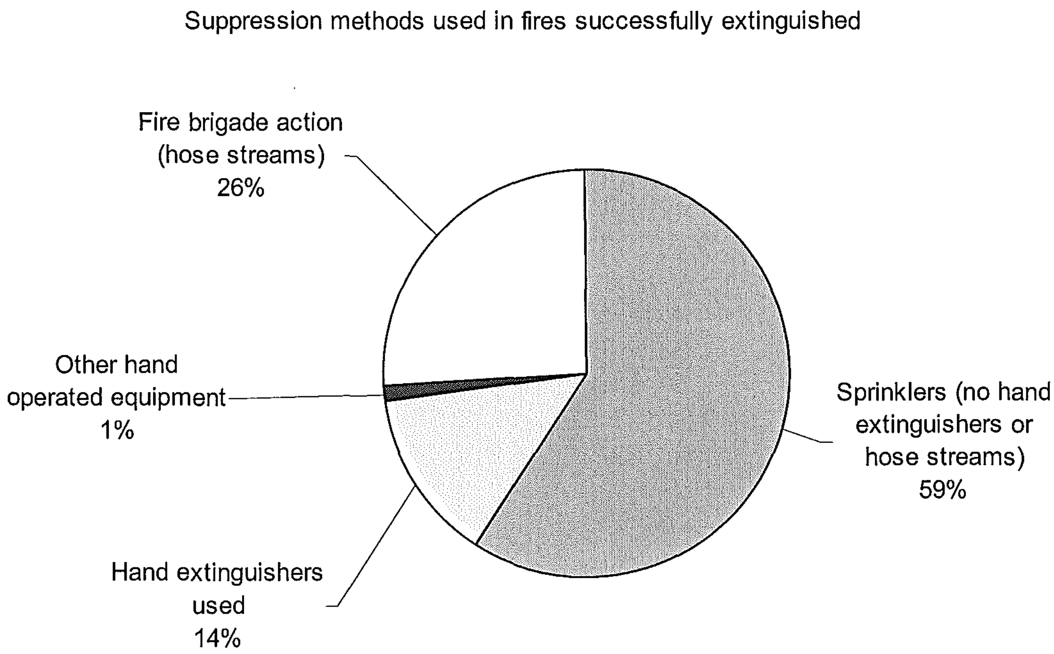


Figure 6.1 Types of fire suppression used to extinguish fires in sprinklered buildings

Sprinklers extinguished nearly 60% of fires; hand held equipment operated by either the fire brigade or building occupants were used to extinguish 40% of fires. This is not to say that the fires in which other methods were used would not have been effectively controlled by the sprinkler system, but to point out that the statistics include the contributions of these external influences. Given that the sprinkler activation (which occurred in all fires studied by Marryatt) would have automatically alerted the building occupants and/or the fire brigade while the fire was relatively small, it is not surprising to have external involvement in fire suppression.

6.3.5 Application of results: reliability issues

It is assumed for the purpose of this research that if a fire does not reach flashover or full development in the enclosure then it does not adversely affect the stability of the steel structure. The definition of flashover varies. One definition or attribute of flashover is when the temperature in the upper gas layer reaches around 500 to 600°C. As the limiting steel temperature for steel members designed in accordance with New Zealand and Australian design standards is typically at least 500°C this assumption appears reasonable. (It would be the responsibility of the structural design engineer to verify whether or not a particular steel structure would be susceptible to fire temperatures that might be reached prior to flashover, and hence whether or not findings of this report are applicable to that particular structure).

Similarly it is assumed that the fires which were controlled by sprinkler operation had no adverse affect on the performance of the structure. This assumption is more difficult to validate. Some fires in which many sprinkler heads activated may have reached temperatures that could approach the limiting steel temperature of some members. However, given the more typical range of steel limiting temperatures (600°C to 750°C) fires with upper layer temperatures in this range are much more likely not to be controlled by sprinklers. Also, there were significantly fewer cases in which sprinkler-controlled fires activated many sprinkler heads for the types of occupancy and buildings in the scope of this research. Hence this assumption relating to a correlation between sprinkler performance and structure performance also appears reasonable.

Another reason for exercising care when extrapolating the results of Marryatt's study relates to the changing environment in which sprinkler systems are designed, installed, maintained and expected to operate. Building types and occupancies predominant in sprinkler-protected situations over the last 100 years may have changed from those that existed at the time of the survey fires and may change even more to an extent that affects sprinkler reliability. For example office buildings are now more open plan and contain more combustible plastics, etc. This could lead to faster fire growth but countering this is the high reliability of the systems to suppress a fire on activation of only a few sprinkler heads. In Australia and New Zealand 90% of fires activated 4 or fewer sprinkler heads while for the United States this applied to only 77% of the wet pipe sprinkler systems. With this in mind, the effect of changes to materials and surface finishes, and more open plan spaces would appear to have little effect on overall sprinkler effectiveness.

For most of the issues described above there is no way of quantifying the effect. Also, most items are not expected to have a significant bearing on future sprinkler reliability. Therefore, while it is important to keep these potential limitations in mind there is no convenient way of explicitly incorporating them into the analysis given in this report.

6.4 PERFORMANCE-ENHANCING ATTRIBUTES OF NEW ZEALAND SPRINKLER SYSTEMS

There are a number of beneficial attributes of automatic sprinkler systems installed in New Zealand which are different from those in other parts of the world. (J. Fraser, pers. comm.). Six of these are discussed in this section of the report.

6.4.1 Direct connection to the Fire Service

Direct connection of fire alarm systems and sprinkler systems has always been a feature of fire systems in New Zealand.

When fire alarm systems were introduced into New Zealand it was an integral part of their design that they would summon the Fire Service for assistance. Devices were incorporated in the sprinkler and fire alarm system that uniquely identified the particular system of which it was part. The signal was transmitted via the telephone system identifying the building to the Fire Service.

6.4.2 System devices to detect sprinkler activation

In Australia the sprinkler systems use a water driven turbine bell which requires water to be flowing for the alarm to sound and to detect sprinkler activation (i.e. valves need to open before the brigade gets a signal). In New Zealand a series of pressure switches monitor the sprinkler system and signal sprinkler activation. This has a number of advantages when it comes to signalling the status of the sprinkler system. The signal is more sensitive (it doesn't rely on a flow of water through the valve). Also, the pressure differential that is created by over pressurising the sprinkler pipework allows the system to discriminate between a fault (leak) and sprinkler activation. Therefore the system is more reliable to the user and the Fire Service as the faults are identified before they become a sprinkler activation.

Another significant beneficial side effect from using pressure switches (and hence needing to pressurise the sprinkler pipework) is the better sprinkler performance at sprinkler activation.

6.4.3 Higher town main water pressures

New Zealand cities typically have more hilly terrain, so town main water pressures tend to be slightly higher than for similar sized cities in many other parts of the world.

New Zealand sprinkler systems over pressurise the sprinkler pipework network relative to the town main pressure. In New Zealand this means that the actual 'operating pressure' of the sprinkler system may be much higher than the minimum needed in cities in other parts of the world. This higher pressure produces a sprinkler spray pattern which covers a wider area than the minimum listed area and the water droplets are finer.

These benefits combine to produce more effective extinguishment on activation of the first sprinkler and hence a greater likelihood that the first sprinkler will be effective in controlling or suppressing a fire. Sprinkler systems in New Zealand appear to have a better record of controlling fires with activation of one sprinkler than anywhere else in the world.

6.4.4 Main stop valve location and valve monitoring

In the USA many main valve installations are located above ground and outside buildings and are therefore susceptible to interference. The main stop valves are typically not monitored so there is no warning or signal indicating that a water supply has been shut down. Accordingly, a high proportion of the sprinkler 'failures' are due to the water supply being off, either at the main stop valve or within the system itself (internal valves shut). In New Zealand systems, main stop valves are typically located in an enclosure, usually inside buildings and all stop valves are monitored. Hence there is much less chance that the supply will be compromised at the time of a fire due to tampering with stop valves.

6.4.5 Development of the Sprinkler Standard

Insurance interests have dominated the development of sprinkler design rules and the preparation of the sprinkler codes world wide. In New Zealand this dominance changed with the Napier earthquake in 1931. Following the 1931 Napier earthquake, the

Standards Association of New Zealand was created and this introduced a second party into the development/approval process. Although the insurance industry still dominated the development of requirements for sprinkler design the Sprinkler Standard now had the backing and support of two organisations influential in the construction industry.

6.4.6 Standards maintained nationally

Another beneficial aspect of the sprinkler installations in New Zealand has been the inspection of sprinkler systems by the Insurance Council, which has helped to maintain a level of quality and consistency of systems. Also, in New Zealand the insurance industry has conducted its work nationally, to give a level of uniformity throughout the entire country that is difficult to provide across a range of various states such as in Australia and USA.

In New Zealand the Insurance Industry influence extended to approving the town main water supply as being acceptable for fire fighting. Because of this national control exercised by the Insurance Council of New Zealand, the statistics on sprinkler reliability that have been obtained for New Zealand as a whole are applicable to any area in the country because all areas have been under the same control regime. Overseas, where each different state has its own particular requirements it is more difficult to obtain some level of national consistency and hence to be confident that sprinkler reliability statistics apply in any given area.

Another benefit resulting from the earliest direct fire brigade connections (and due to the clockwork system used in the past) is that the fire alarm systems are checked on a regular (weekly) basis, to ensure that the mechanism was wound and that the line to the exchange was intact and working correctly. This was considered necessary to ensure the reliability of the signal to the Fire Service, although now of course the systems are much more reliable. A consequence of this regular checking is a high level of quality control for the other systems: the sprinkler system is checked for a drop in pressure (indicating leaks), the fire panel is checked for circuits not working (defects) and routine preventative maintenance issues are attended to (e.g. checking the charge in batteries, etc.)

Bi-annual surveys were also carried out, as today, which are critical to checking the ongoing performance of the system. For example, this is the one of the few ways to check for blockages in the system. On several occasions surveys have picked up shut street valves (lower pressure readings than expected). As buildings are altered the sprinkler system is not necessarily altered to suit. The bi-annual surveys are useful in identifying discrepancies in detector and sprinkler coverage.

In the past the Territorial Authorities have been required by legislation to provide water supplies for Fire Service use and have traditionally been very supportive of this. Now though, as private ownership is becoming more common there is a trend towards lower pressures to conserve water and protect the infrastructure. In future years legal agreements may need to be obtained to ensure adequacy of supply, particularly with privately owned water suppliers.

Under the latest building control system in New Zealand, it is vitally important to implement the check of items on the compliance schedule as required to gain a building warrant of fitness, to provide the same level of back up that was available under previous design and management regime for sprinklers and fire alarm systems.

6.5 OTHER STUDIES RELEVANT TO SPRINKLER RELIABILITY

6.5.1 Sprinkler Downtime due to Building Alterations

Sprinkler downtime due to alterations of the internal building layout (and usually the sprinkler system as a consequence) has been identified as one of the main contributors to a loss of reliability in shopping centres (Bennetts et al, 1998). This is also true for other occupancies involving predominantly leased space, such as office buildings. Thomas et al (1992b) identified this as one of the causes of operational failure of the sprinkler system in the risk assessment for the 40 level office building at 140 William Street. Obviously this impact on sprinkler reliability is greater in buildings with frequently occurring tenancy alterations.

The frequency with which tenancies change and consequently alter the sprinkler system varies depending on the occupancy type, tenancy area and location, the building area, the urban area in which the building is located and external factors, such as the state of the economy and the local leasing market. This frequency can be estimated from historical records or estimated from observation. However, as a general predictive value this is, at best, only an estimate of the order of magnitude that this factor introduces into the reliability assessment for a specific building.

Some examples are given below.

Data from the risk assessment study for 140 William St (Thomas et al 1992b) suggested that, on average, occupancy changes that require alteration of the sprinkler system occur 15 times per year. This is in a 40 level building of which 34 levels are occupied. It was assumed that each alteration involved sprinkler isolation for 4 days and that in 5% of cases contractor error might cause a delay of an extra day to re-pressurise the sprinkler system for that floor that had been isolated. Hence the total proportion of time that the sprinklers would be isolated is approximately 1.4×10^{-3}.

More recent data collated by Bennetts et al (1995) surveyed 24 high-rise office buildings in Australia. For each building data was obtained giving the frequency of sprinkler isolation, the average duration of sprinkler down-time, the total number of levels and the average number of levels affected by shutting down water to the sprinkler riser. In New Zealand, buildings of the height in that survey would all require monitored isolate valves at each floor, so the extent (floor area) of isolation is likely to be less than for the Australian experience. Taking this New Zealand difference into account, more than 95% of the buildings had an average sprinkler isolation time of less than 1.0×10^{-3} per year. For the Australian data the value below which at least 90% of the values lie is nearer 5.0×10^{-3} per year.

In the same study (Bennetts et al, 1995) data was obtained for sprinkler isolations in carpark levels in multi-level multi-use buildings. An analysis of this data shows that the average sprinkler isolation time is less than 2.3×10^{-4} per year for this type of occupancy – an order of magnitude less likely than for office or retail occupancies.

Data on shopping centres is summarised by Bennetts et al (1998) following detailed surveys of a number large shopping centres there. The frequency of sprinkler alterations is much higher in the specialty shops than in department stores, because lease arrangements tend to be for shorter terms and there is naturally a higher turnover of tenants. Average values for the proportion of time per year for sprinkler isolations are between 1.1×10^{-2} and 1.5×10^{-2} per year for specialty shops and 5.0×10^{-3} per year for the major department stores.

One factor which minimises the risk associated with sprinkler downtime is that in New Zealand all isolate valves installed in sprinkler systems are monitored by the fire alarm panel. This monitoring is also linked back to the central monitoring station in New Zealand that is therefore aware of all cases where isolation valves have been closed and automatically notifies a contractor if a valve is not opened after the agreed shutdown period. More information on this monitoring service is given in the next section.

6.5.2 Data on Sprinkler Isolation from AFA Monitoring

In New Zealand effectively all sprinkler systems are monitored via a direct telephone link to the Fire Service monitoring system run by AFA Monitoring. This monitoring system is centralised for the whole country with activations of sprinkler and fire alarm systems relayed back to the appropriate local fire station. This monitoring service is also made aware of all cases in which a (sprinkler) system is isolated from the monitoring system for whatever reason (usually servicing, maintenance or alteration). Not all instances of isolation mean that the sprinkler system is not functioning. In some cases the systems being altered still have water in them and would be capable of operating as a sprinkler system if necessary (the benefits of this are discussed briefly in section 6.3 above and more fully in Marryatt (1988)). In other cases, alterations to part of a sprinkler system leave the remainder of the system operational.

Data has been supplied by AFA Monitoring for one month. This data is representative for any month because there is very little variation each month in the number and length of system isolations (R. Stewart, pers. comm.). The proportion of systems isolated for various times is shown in Figure 6.2.

Analysis of this data reveals that the number of isolations in one month was 1.87 times the number of monitored systems. This number of isolations can be explained in part by the requirement in the New Zealand sprinkler standard for monthly testing of various aspects of the sprinkler system as part of routine maintenance. However, clearly there are many systems being isolated more than once in that month. For example, there were

(441) more isolations of up to 10 minutes duration than the total number of monitored systems.

In most cases the method of monthly testing does not prevent the sprinkler system from functioning as intended, so it would be conservative to assume that for this period the sprinkler system is 'unavailable'. Isolation of a sprinkler system for 10 minutes per month corresponds to a reliability of 0.9998/year.

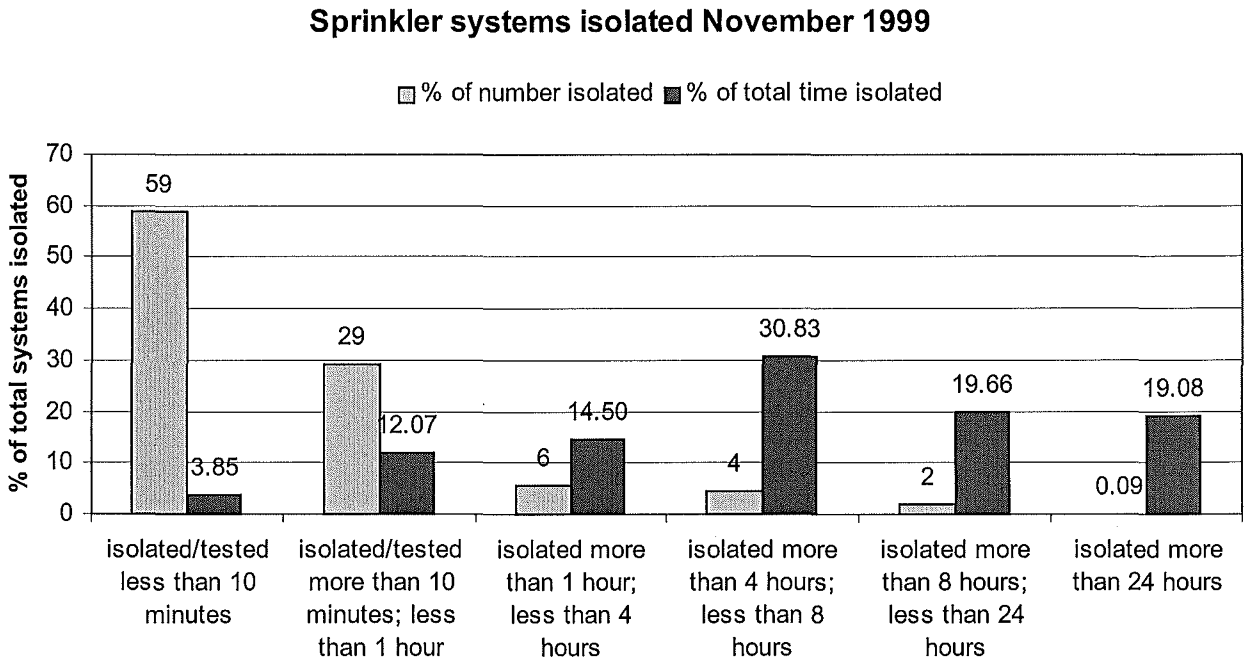


Figure 6.2 Duration of sprinkler system isolation from AFA Monitoring

For this report we are interested in isolation of commissioned systems to the extent that this affects the impact of fire on structure. The data provided by AFA Monitoring describes the reason for isolation of systems isolated for more than 24 hours. More than 50% of the total time for isolations of more than 24 hours is attributed to sprinkler systems in buildings still under construction, or to electrical faults in systems that were otherwise still functioning effectively as sprinkler systems. These reasons for the isolations are regarded as atypical and therefore do not contribute to an assessment of sprinkler reliability. Because the circumstances of these isolations are outside the scope of this report their duration times have been disregarded.

For this study, a factor of 0.8 applied to the isolation duration times provided by AFA Monitoring is assumed to conservatively account for the fact that not all sprinkler systems were completely isolated in terms of:

- area covered, or
- reduced capability of the sprinkler system to operate, and
- actual duration of isolation of the sprinkler system compared with the time of isolation recorded by AFA Monitoring

Assuming that the monthly data is representative of annual sprinkler reliability and deducting the time for isolations known to be outside the scope of this report, the total duration time of sprinkler isolations for the month is 6961 hours. Applying the factor of 0.8 to account for less than total isolation of sprinkler capability reduces this value to 5569 hours per month for all sprinkler systems monitored by AFA (advised by AFA to be 5400).

Hence the mean expected isolation time for any one sprinkler system is 5569x12/5400 = 12.4 hours per year. This corresponds to an average reliability of 0.9984/year, and is the value used in this report. Hence the annual probability of isolation of a sprinkler system due to maintenance or tenancy alterations is s $1 - 0.9984 = 1.6 \times 10^{-3}$.

7 SPRINKLER WATER SUPPLY RELIABILITY

7.1 INTRODUCTION

This section of the report is concerned with the reliability of external water supply sources. In this context, 'external' refers to a water supply that is beyond the boundaries of the property concerned and which is beyond the direct control of the building owner, sprinkler system maintenance, etc.

The New Zealand sprinkler standard NZS4541:1996 classifies water supplies for sprinkler systems as follows, in order of decreasing reliability:

Class A: dual supply, one of which is independent of the town main network. The second supply is usually an on-site tank.

Class B: dual supply; usually two connections to independent parts of a town main water supply. 'Independent' in this context refers to sections of the supply network that can be independently isolated (for maintenance or repair).

Class C: single supply; usually a single connection to a town main water supply

The town main water supply network is usually relied on for sprinkler water supplies. Amendments to the sprinkler standard in 1996 forbid buildings more than 25 metres high from relying on a Class C water supply. Buildings constructed in the central part of New Zealand, where the risk of earthquake is higher than in other parts of the country, and which are higher than 25 metres are required to have a Class A water supply. However, these sprinkler standard water supply restrictions are not mandatory in order to comply with the Building Code and they generally do not apply retrospectively for buildings to maintain a certificate of compliance with the current standard.

The likelihood of a sprinkler system being without water is low. The risk of a water supply not being available at the time of a fire which activates the sprinklers is very low. Clearly, the reliability of sprinkler water supply is greater if there are two independent connections to the town main reticulation (rather than only one). In the infrequent event that part of the system needs to be isolated for whatever reason (repair of breakage, connection of new supply, maintenance, etc) the water supply to the sprinkler system is maintained. A Class A supply, which has an approved alternative independent water supply is even more superior in terms of reliability.

It is important to gauge the reliability of these external water sources, since all the care and attention to detail that may be exercised by a building owner is of no benefit to a sprinkler system at the time of a fire if there is no suitable water supply available. This is one of the most frequently cited reasons for not relying on a sprinkler system to control all outbreaks of fire.

The importance of the more reliable sources (Class A or B) is a function of the frequency and duration that the town main supply could be inadequate or unavailable.

7.2 TOWN MAIN RELIABILITY

To gauge the significance of potential interruptions to the town main, data collected by Metrowater, the municipal water supply authority in Auckland City, has been analysed to indicate the frequency of possible temporary shutdown of any part of the town main water supply. The data supplied covers the period December 1997 to April 2000, listing every recorded unplanned and planned shutdown in the Metrowater water supply network. Unplanned shutdowns are mainly for repairs to faults or breakages. Planned shutdowns are for maintenance, scheduled repair and replacement, alterations and new connections, but data for these have only been recorded since late 1998 (M. Blanch, pers. comm., 2000). For each shutdown the date, duration and reason for the shutdown are recorded; in many (but not all) cases the number of customers connections that are affected by the shutdown are also listed.

The data has been analysed in two ways: firstly using all of the data and ignoring the fact that planned shutdowns were not recorded until late 1998; secondly using only the data from November 1998 to April 2000. A summary of key results is given in Table 7.1.

Clearly there is very little difference between the results from the two analysis methods and the probability of the town main water supply not being available is very low.

Table 7.1 Summary results from analysis of town water main shutdowns (planned and unplanned), Auckland City.

Total number of water supply connections (customers)	115,000	
Average number of connections affected by any one shutdown	47	
	data analysis method 1	data analysis method 2
period covered	November 1997 to April 2000	November 1998 to April 2000
number of shutdowns in period	1256	893
average length of shutdown	2.9 hours	2.8 hours
number of shutdowns less than 5 hours duration	1185 (94%)	875 (98%)
number of shutdowns more than 5 hours duration	71 (6%)	18 (2%)
average length of shutdown less than 5 hours duration	2.6 hours	2.7 hours
average length of shutdown more than 5 hours duration	7.9 hours	9.8 hours
frequency of water shutdown per connection (customer)	7.3×10^{-5}	8.1×10^{-5}
expected shutdown time per year, per connection (customer)	38 minutes per year	43 minutes per year
water supply reliability, per year	0.99993 (99.993 %)	0.99992 (99.992 %)
annual probability of water supply not being available (= 1 – reliability)	7.0×10^{-5}	8.0×10^{-5}

This water supply reliability is assumed to be independent of any reduction in reliability due to alterations to the sprinkler system as recorded by AFA Monitoring (see section 6.4.2 herein). In a few cases the alterations to the sprinkler system would also coincide with alterations to the water supply, so the same event would be recorded in two different ways. However, it is conservative to assume that sprinkler isolation and water supply shutdown are separate independent events.

However, the above analysis describes average values only without specifically quoting monthly reliabilities that take into account seasonal variations (breakages due to ground movement and more planned maintenance during the summer months both increase the likelihood of shutdowns during this season). This does not affect the average annual reliability of the water supply derived above, but this annual average value will not necessarily be accurate for a particular month or season. This, of course, is consistent with the approach used with average values for wind speed for structural design.

The above analysis also does not cover periods of drought, etc which could affect reliability of supply. However, in most modern towns and cities the town main supply has been designed to cater even for extreme water supply conditions and it is not expected that the entire town main supply would be shut down completely due to lack of water. The analysis also does not account for shutdown of the supply to the sprinkler system on the sprinkler branch line or at the sprinkler stop valves. Such maintenance work is of course necessary and will add to potential risk that the system may not be supplied with water as intended. This risk is described in the section 6.5.1 in this report, dealing with sprinkler reliability.

While it is obvious that the results pertain to the water supply network in Auckland City, they may not necessarily be applicable in other parts of New Zealand. However, they give an indication of the order of magnitude of water supply reliability against which other city supplies could be compared.

The other significant event that has not been addressed is the risk and consequence of earthquake with respect to water supply. This is discussed in more detail later in this report.

Some data on water mains breakdowns is presented for Melbourne suburbs (Bennetts et al, 1995). It is reported that 90% of failures are repaired within 5 hours or less, which is consistent with the data obtained for Auckland City (around 95%). The expected reliability of the water main is ascertained as shown in Table 7.2.

This result is very similar to the results obtained for Auckland. This is not surprising, given that both cities, being large, will have a need to a responsive workforce who can identify and repair faults quickly so as to reduce disruption from shutdowns to a minimum.

Table 7.2 Summary results from data on town water main breakdowns, Melbourne City

frequency of water shutdown per connection (customer)	5.8×10^{-5}
expected shutdown time per year, per connection (customer)	31 minutes per year
water supply reliability, per year	0.99994 (99.994 %)
annual probability of water supply not being available	6.0×10^{-5}

In comparison, the fire risk assessment carried out for the building at 140 William St (Thomas et al, 1992b) assumed that the probability that any one of the two town main supplies serving the sprinkler system being out of service was equivalent to 5 days in 100 years. This gives a probability of 1.4×10^{-5} (water supply reliability for one town main of 0.99999) which is slightly more optimistic than the more recent data above for Melbourne.

Marryatt (1988) has recorded the type of water supply used for the various sprinklers systems in which fires occurred. Most (61%) of fires occurred in systems with a single town main supply. The rest (39%) occurred in systems with either two town main connections, or a combination of tanks and pumps supplying water from one or two independent supplies. The proportion of fires in systems with only one supply is a measure only of the relative proportion of the two main types of supply. Given the low number of fires that were not controlled by sprinklers and the fact that so many of them were by systems with only a single water supply, the provision of a dual town main supply to increase reliability of the sprinkler system does not appear justifiable. Systems with an increased water supply reliability do not, in fact, appear to have a lower probability of sprinklers 'failing to control a fire'. More than 95% of the buildings did not have an independent supply and were totally reliant on the town main supply.

7.3 SPRINKLER BOOSTER PUMP RELIABILITY

One area in which the data collated by Marryatt (1988) is not necessarily valid for future sprinkler installations is the number of systems that require booster pumps to achieve the necessary water supply pressure. With increasing numbers of high rise buildings there are now more sprinkler systems dependent on the operation of booster pumps for effective sprinkler fire suppression.

In the risk analysis carried out for the refurbishment of the 40 level office building at 140 William St in Melbourne, Thomas et al (1992b) assessed the probability of failure of pump components as they affected the reliability of the sprinkler water supply. In that study the outcome of relative risk for three building scenarios was more important than absolute values of reliability, but the failure probabilities give an indication of the magnitude that this aspect of sprinkler failure can have on overall reliability. The values are highly dependent on the monitoring and maintenance regime for the sprinkler system, as this can significantly alter the probability that a component will work at the time of a fire.

It is of interest to compare probabilities of failure in the 140 William St study for a system that complies with the minimum requirements of the Building Code of Australia (BCA building) with those for a building subject to more frequent maintenance (the "refurbished" building). Based on data from Thomas et al (1992b) for various types of failure, indicative values for pump reliability have been derived as given in Table 7.3. Types of faults included faulty diesel or electric pumps, faulty pressure switches to start the pump, failure of a diesel pump to start (faulty batteries) and unavailability of mains power for an electric pump.

Table 7.3 Indicative (annual) probability of failure for diesel and electric pumps based on Australian data

	BCA building	"Refurbished" building
probability of electric pump not working	7.0×10^{-2}	1.5×10^{-3}
probability of diesel pump not working	1.2×10^{-1}	1.6×10^{-3}

The differences in failure probability of more than an order of magnitude can be attributed to the differences in maintenance. These will vary depending on the building, the building owner and manager, thoroughness of the maintenance and testing organisation, regulatory requirements, etc.

In New Zealand the sprinkler standard (NZS 4541, 1996) and fire alarms standard (NZS 4512, 1997) both require regular testing and maintenance. Furthermore, with the introduction in New Zealand in 1992 of annual building Warrants of Fitness, the fire safety systems are required to be independently inspected and certified to the Territorial Authority that they are being maintained. This has increased the base level reliability of these systems in New Zealand, although the extent of this improvement is difficult to quantify.

Using the data obtained for the Australian study but modifying it to suit the stricter maintenance regimes required by New Zealand standards, indicative failure probabilities for pumps in New Zealand sprinkler systems are as shown in Table 7.4.

Table 7.4 Suggested (annual) probability of failure for diesel and electric pumps in New Zealand sprinkler systems

	New Zealand sprinkler systems
probability of electric pump not working	2.0×10^{-3}
probability of diesel pump not working	1.5×10^{-3}

These values are consistent with the expected relativity to the Australian values. However, more accurate data on actual performance of New Zealand sprinkler pump systems is needed to establish the accuracy of these suggested probabilities.

The impact this has on sprinkler reliability will vary depending on the particular system. If a sprinkler system has one water supply and this needs to be boosted by a pump to provide adequate pressure, then the reliability of the sprinkler system appears to be highly dependent on the pump reliability. If a system has two water supplies, then this effect is significantly reduced as long as both supplies are not dependent on the one pump (not permitted by the New Zealand sprinkler standard). This point is illustrated in the example in Figure 7.1.

Table 7.5 Reliability of sprinkler water supplies for different combinations of town main, tank and booster pumps.

Assumptions (annual probabilities):	
probability of town main water supply not being available	8.0×10^{-5}
probability of electric pump not working	2.0×10^{-3}
probability of diesel pump not working	1.5×10^{-3}
probability of no tank water supply	5.7×10^{-5}

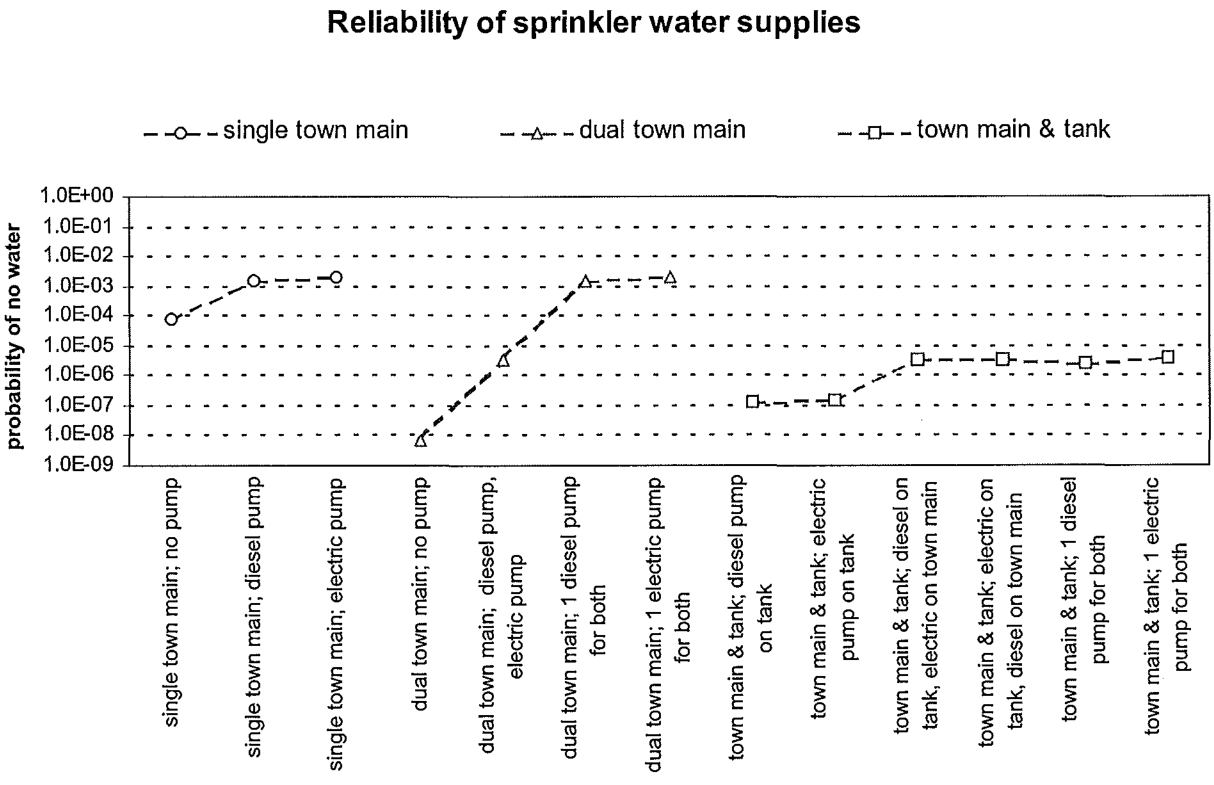


Figure 7.1 Reliability of sprinkler water supplies

7.4 SUMMARY – SPRINKLER WATER SUPPLY RELIABILITY

Based on data obtained for the metropolitan areas of Auckland and Melbourne and assuming that this can be used generally for urban centres in New Zealand, an average reliability for the town main water supply of 0.9992/year is used in this report. This gives an annual probability that the sprinkler system will not have a town main supply of approximately 8.0×10^{-5} when reliant on a single connection.

For sprinkler systems that draw from either of two town main supplies that are truly independent, the probability that the sprinkler system will not have at least one town main supply is very low – approximately 6.4×10^{-9} using the most pessimistic data for New Zealand but excluding the influence of earthquakes.

If booster pumps are needed for adequate water pressure then reliability drops slightly, depending on whether the system is fed from a single town main or from more than one sprinkler water supply.

Clearly, the probability of the town main water supply not being available at any given time is low. When considered as an independent event in conjunction with the probability of a fire start, the probability is even less. Hence, as long as the loss of town main water supply is a statistically independent event from both the cause of a fire start and any other reason for the sprinkler system not operating as intended, the probability that the town main water supply is not available to supply a sprinkler system at the time of a fire, for the purpose of ensuring adequate structural performance in fire is very low.

The need for sprinkler boost pumps to achieve the required pressure reduces the probability that water will be available to the sprinkler system at the required pressure. Clearly if two independent town main water connections are provided for improved supply reliability, then two independent sprinkler boost pumps are needed to maintain this improved reliability. Providing only one pump to serve both water supplies is not significantly more reliable than a boosted single town main supply. Based on the probabilities of pump failure (and reliability of electricity supply) assessed in this report it appears to make little difference whether diesel or electric pumps are used. Notwithstanding the above comments, the reliability of water supply even with booster pumps is very high (not more than 0.2% probability of failure per annum).

The available pressure from the town main is also not a deterministic value. Water pressures vary during the day, during the year and from year to year. To reduce wastage from leaks in ageing water supply networks there has been an increased tendency to reduce water pressures generally. This has an adverse impact on sprinkler systems that are installed without booster pumps in areas where the town main ambient pressure is close to the minimum design pressure for the sprinkler system. For these systems this has the effect of reducing the actual town main reliability from that reported above.

8 FIRE FOLLOWING EARTHQUAKE

8.1 INTRODUCTION

The statistics collated by Marryatt (1988) do not cover any situations of fire following earthquake. Fortunately, the occurrence of large earthquakes is rare and reports from recent minor and moderate earthquakes in New Zealand confirm that none of these have resulted in significant fires in buildings. However, the risk in the more seismically active regions of New Zealand is relatively high and needs to be considered.

In the earthquake scenario events are no longer statistically independent: an earthquake may damage either the sprinkler water supply (town main or water tank) or the sprinkler system within a building (pumps, pipework, etc) and also be the cause of a fire start in a building. As fire safety design procedures become more sophisticated and greater reliance is placed on active systems such as sprinklers, redundancy and reliability concerns become far more important. For the case where sprinklers may offer an acceptable trade-off against passive fire protection of a steel structure, the scenario of fire following an earthquake needs to be considered.

As a consequence of the earthquake ground motion, buried pipework in a town main water supply network and water supply reservoirs can be damaged, threatening the availability of water from the town main. The New Zealand sprinkler standard (NZS 4541:1996) recognises this threat, requiring buildings more than 25 metres high in seismically active regions to have a Class A water supply – two independent water supplies, with the primary supply not reliant on the town main.

The response of a building to the earthquake may disrupt the integrity of the sprinkler system in the building and hence its ability to perform as required to control any outbreak of fire. Accordingly, sprinkler systems must be designed to resist these earthquake-induced forces and displacements. In almost all installations, sprinkler systems should be regarded as 'critical proprietary equipment' as classified by the New Zealand Loadings Standard (NZS 4203,1992) because of the life safety function they provide, a view shared by Botting and Buchanan (1998). (In rare circumstances a sprinkler system may be provided for property protection only and offer minimal improvement to life to safety. However, the expectation of property protection normally still applies in the event of an earthquake, so the same functionality is required even if this benefit is not for life safety.

This classification requires the systems in buildings to be designed to resist a level of loading corresponding to an ultimate limit state earthquake and remain operable. The exceedance probability of such an event can be taken as 0.10 for a nominal 50 year design life (NZS 4203, 1992), equivalent to an annual exceedance probability of approximately 0.002. In practice, this expectation is often not realised because structural engineers with the expertise to determine seismic-induced forces and to design suitable seismic restraints for these systems are almost never involved in this aspect of design.

In New Zealand, standards specifying requirements for seismic restraint of building services have existed for more than 17 years (NZS 4219:1983). The most recent version of the New Zealand sprinkler standard (NZS 4541:1996) also specifies in detail how to provide appropriate seismic restraint to sprinkler pipework. Observations of poor performance of building services in earthquakes prompted a research programme at the Building Research Association of New Zealand to investigate how New Zealand systems might perform. Audits of five buildings in service (Beattie, 1999) showed that considerable attention had been paid to providing seismic restraint to services (often during upgrades carried out some time after completion) even though a survey showed that implementation at the design stage is not widespread. In shake table tests, carried out to simulate earthquake effects on seismic restraints to a typical sprinkler pipework network, the system performed well. Although some bending of sprinkler supports occurred, they provided more lateral support than expected and pipework remained intact.

Buildings designed to the New Zealand Loadings Code (NZS 4203:1992) are required to withstand the smaller (more frequently occurring) earthquakes with no damage to the structure and no significant damage to the non-structural elements of the building that would render it unserviceable. For this (serviceability) limit state level of earthquake building services are expected to remain fully functional, so there should be no concern for sprinkler system performance provided the systems have been designed and installed to meet current standards.

For a less frequent but larger (ultimate limit state) level of earthquake, some damage to the structural and non-structural elements may occur. In this event, the principal objective is clearly focussed on life safety, so damage to property (either the building owners or that of others) is a secondary concern. For earthquakes not strong enough to cause damage to structure, the sprinkler system is also expected to remain operable.

8.2 PERFORMANCE REQUIREMENTS IN FIRES FOLLOWING EARTHQUAKE

Two of the main concerns relating to fires following earthquakes are:

1. outbreak of fire in a building immediately following an earthquake and its effect on occupants who need to evacuate safely

2. spread of fire to adjacent buildings in built-up areas, that may develop into a large-scale conflagration if this pattern of fire spread continues.

This latter problem is the most obvious and visible outcome, as the ability of fire-fighters and emergency services to respond will be stretched to capacity as a result of the earthquake. Damage to the town main water supply could also seriously limit fire-fighters' ability to prevent fire spread to neighbouring buildings in most cases. Large scale fires can occur with devastating results.

Apart from the support function provided to external fire rated elements of construction, the performance of a steel structure, and more specifically whether or not the structure is provided with passive fire protection does not affect the likelihood of large scale conflagration following an earthquake. More importantly, the design and redundancy built into the town main water supply is a lifelines issue for municipal supply authorities to address.

Given the relatively low probability (in most cases) of a large earthquake and the nature of the circumstances that exist immediately after, it is appropriate to review the performance requirements for the structure that should apply in the event that a fire also occurs. The New Zealand Building Code makes no reference to performance requirements that apply in this unlikely combination of events.

The performance requirements of both the structure and of the fire safety systems should vary depending on the building, the type of occupancy and the importance of the facility being operational immediately after an earthquake. Approved verification methods for structural design (NZS 4203, 1992) specify different design parameters, depending on the post-disaster importance of the building. However, similar design objectives recognising post-disaster performance are not embodied in the functional requirements for fire safety design.

Three general post-earthquake performance objectives relating to life safety, property damage and fire spread proposed by Robertson and Mehaffey (1999) could be adopted. A range of varying criteria for design of fire safety systems is also proposed, dependent on the building function and hence the required performance level. That study also describes a very useful analysis method which incorporates empirical assessment of the main factors affecting post-earthquake fire safety, as an alternative to an engineered risk assessment approach.

For the building structure, the following performance objective is suggested specifically for the case of fire following earthquake.

> The building structure is to remain stable after an earthquake (and during any consequent fire that may occur) for the time necessary to ensure that building occupants have safely evacuated and search and rescue can take place to rescue trapped or injured occupants.

Steel-framed buildings designed for seismic resistance in accordance with modern procedures, such as the Loadings Standard NZS 4203 (1992), the New Zealand Steel Structures Standard NZS 3404 (1997) and recommended seismic design procedures (Feeney and Clifton, 1995) are designed to resist structural collapse even when subjected to extreme seismic loads. The above performance objective is therefore not intended to apply to the specific case where search and rescue is conducted in buildings already collapsed. However, high-rise buildings or those with large numbers of occupants may take much longer to evacuate than expected, particularly if occupants are injured and require assistance or if escape routes are blocked by debris. In these extreme cases, it is expected that fire separations supporting or enclosing escape routes may need to withstand a complete burnout in an adjacent firecell. Also, fire separations that control the spread of fire to floors above (the floor slab, walls enclosing vertical shafts and ducts and penetrations in these fire separations) must also be maintained for the length of time that it takes for all occupants to evacuate via protected escape routes. Structural members whose performance in fire directly affects the performance of these fire separations require specific attention and may need to satisfy the same performance requirement. If the earthquake is severe enough to damage the sprinkler system in a building then it is likely that there will also be significant damage to building contents, non-structural components (which are not required to be designed for the same high level of seismic forces) and possible damage to the structure itself. Such damage is likely to occur in most buildings throughout the earthquake-affected region, to varying degrees. Under these circumstances, when the earthquake has already caused significant damage to buildings and property, it is inappropriate to require buildings to be designed to minimise damage to other property from fire to the same extent as if the earthquake had not occurred. A reasonable degree of fire separation will usually be maintained in spite of earthquake damage, but it would not be acceptable to require extra building cost to ensure that this more onerous performance requirement is achieved. This is certainly true with respect to the need for passive fire protection to a skeletal steel structure. Providing passive fire protection is the least beneficial solution for minimising damage to other property since it only helps the structure, not the building contents or fire separation walls. Even the support afforded by the structure to floor slabs and walls is not significantly enhanced in terms of improving protection to other property.

Control of fire spread to other property that may occur within the same building (e.g. strata or unit titles) is expected to be provided by the same fire separations that are needed to control vertical fire spread while occupants are escaping from the building. Clearly the time frames may be different: control of vertical fire spread to restrict damage to other property normally requires a fire separation to withstand a total burnout of the relevant firecell whereas the fire resistance needed for safe evacuation may be less than this. However, in this research it has been assumed that the differences are small and that the construction provided for safe evacuation will provide a sufficiently high degree of protection (given the nature of the situation) to other property in the same building.

Hence it has been assumed for this report that control of fire spread to other property after an earthquake, while desirable, should not incur additional design effort or cost. The performance objectives that exist for general fire design are considered reasonable to control the risk of uncontrolled large-scale fire spread, at least between the engineered building structures that are within the scope of this report. Therefore the structure needs to remain stable to provide support to external fire separations only to the extent that it also needs to avoid collapse during an earthquake for life safety reasons. Usually the performance that satisfies the latter will also satisfy the former.

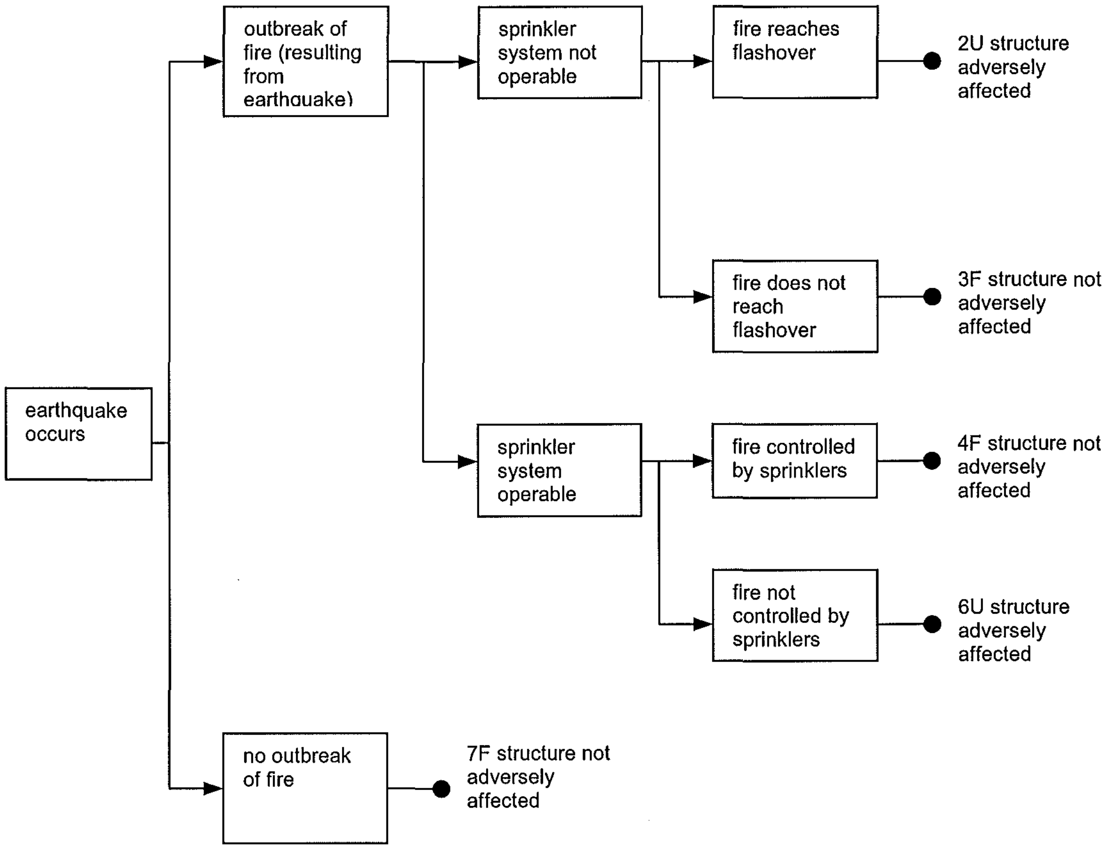
8.3 CALCULATION OF RISK

The procedure of Robertson and Mehaffey (1999) does not take into account the probability of a fire following earthquake, hence assumes this will occur. It assesses a 'seismic fire factor' used to modify a design fire for evaluating the performance of the building to meet the 'fire following earthquake' performance criteria.

This section discusses specific risks associated with fire following an earthquake, including the likelihood of a fire start in a building and its growth to flashover.

A risk assessment model based on events affecting structural performance has been developed for the express purpose of evaluating the effect of sprinklers on performance of structure in a fire following an earthquake. The event tree for this model is shown in Figure 8.1.

Figure 8.1 Event tree for the effect of fire following earthquake on structure



The occurrence of an earthquake changes the usual risk scenarios considered in preceding sections of this report. An attempt has been made to quantify the vulnerability of the fire safety of the structure when dependent on external (municipal) water and electrical supplies for sprinkler operation. The most useful sources of data are reports of damage from investigations following earthquakes. However, damaging earthquakes are even less frequent than large fires, so the available data on the risk of damage to these items is scarce. Therefore, the probabilities associated with the various events cannot be determined accurately.

Values assessed using engineering judgement are given in Table 8.1, taking into account interdependence of events. The background to the derivation of these values is discussed later in this section. Unless noted otherwise, values are based on subjective review of reports on earthquake damage and fires following earthquakes (EQE, 1989, 1995; Aurelius, 1994; Borden, 1997; Fleming, 1998; Botting and Buchanan 1998, 2000; Robertson and Mehaffrey 1999; Tong, 1999)..

Table 8.1 Input data for calculating probabilities of event tree outcomes

	Description	Value
P(A)	Annual exceedance probability of earthquake, taken as that for ultimate limit state earthquake from NZS 4203 (approx.)	0.002
P(B)	Conditional probability of outbreak of fire, given earthquake occurs	0.1
P(C)	Conditional probability that sprinkler system is not operable after an earthquake, given earthquake occurs [a] Class A water supply in accordance with NZ sprinkler standard Class B or C water supply with electric booster pump Class B or C water supply, no booster pump required	 0.68 [b] 0.99 [c] 0.88 [c]
P(D)	Conditional probability that fire reaches flashover, given earthquake occurs [d]	0.70
P(E)	Given that the sprinkler system is operable, the probability that it can control an outbreak of fire [e]	0.99
P(F)	Conditional probability that passive fire protection remains in place effectively undamaged after an earthquake [f]	0.90

Notes:

a. Successful sprinkler operation relies on pipework integrity, availability of town main or tank water supply, availability of electricity for electric booster pumps, availability of diesel pump and fuel

b. Assumes tank is primary water supply with diesel booster pump as required by NZ sprinkler standard (NZS 4541, 1996) in moderate to high seismic regions; this value incorporates probability of sprinkler pipework integrity failure

c. Assumes water supply is dependent on either town main or electric booster pump; this value also incorporates probability of sprinkler pipework integrity failure

d. In normal circumstances the probability of fire reaching full flashover is estimated to be 0.2 (refer section 5.2). With building contents displaced and a greater likelihood of favourable ventilation following an earthquake this probability is likely to be much higher (assumed 0.7). This assumes no attendance and suppression by the fire brigade.

e. Probability nominally reduced from that assessed in section 6.3.3 to account for possible shielding from displaced contents; it is assumed that a fire large enough to activate sprinklers will continue to grow and reach flashover if not controlled by sprinklers

f. Estimated value based on flexible sprayed fire protection and knowledge of the local member deformations expected in yielding regions of seismic-resisting structural elements; this also incorporates a small probability (0.05) that the passive fire protection is never applied correctly in the first place, at the location of a fire

The type and extent of damage reported in these references is assumed to be indicative of that which might be expected for the design level earthquake considered herein. In situations where damage is not widespread there can be a tendency to overestimate the extent because the references focus on damage. Examples of satisfactory performance (no damage) are seldom mentioned.

One of the key factors affecting the outcome of this risk assessment is the probability of a fire starting in a building as a result of an earthquake. For this report, which is concerned about the performance of the steel structure in a building protected by a sprinkler system, the more relevant fires following earthquakes are those that occurred in modern urban environments.

Some details of fire starts in buildings following earthquakes are reported by Aurelius (1994), EQE (1989, 1995) and Borden (1997). In many cases, fires appear to have occurred predominantly in housing and residential areas. Post-earthquake fires in the types of buildings to which this report is applicable appear to be less common, although a lack of reported fires (in commercial buildings) could simply be a function of where most people were at the time of the earthquakes. The Los Angeles Fire Department reported that there were 5 to 10 times the normal number of (fire) incidents immediately after the Northridge earthquake (Aurelius,1994).

Fire starts are reported to have been caused predominantly by

- gas leaks
- spillage of flammable liquids
- damage to electrical wiring or appliances causing short circuits.

In cities where there have been reports of building fires after an earthquake, the numbers listed are seldom more than one or two hundred. The number of buildings of the size and type that fit the scope of this report (excluding domestic houses and similar) were in the order of thousands. Estimates based on personal observation of the proportion of buildings affected by fire in the Kobe earthquake, are in the range of 1 in 100 (C. Clifton, pers. comm.). A similar value is suggested for the Northridge earthquake. In an urban area in New Zealand, where of a large proportion of buildings are not anticipated to suffer total collapse due to earthquake and are clad in non-combustible cladding this proportion is also considered appropriate.

Hence the probability of fire start of 0.1 used in this report is regarded as a conservative value which more than adequately caters for any cities with an aged building stock. This excludes the effect of fires that do not originate in the subject building because sprinklers are unlikely to offer much benefit in the event of fire spread from exposure to a large-scale external conflagration.

The likelihood of a loss of sprinkler pipework integrity varies depending on the quality of the system installation and inspection. Although damage to the sprinkler system may not coincide with the location of fire start, unless it is limited to minor leakage only on the uppermost levels in a building it is likely to seriously affect the ability of the sprinklers to control a fire anywhere in a building. Botting and Buchanan (2000) note that 80% of sprinkler systems remained operable after the Long Beach, 1937 earthquake. Most sprinkler systems in the Loma Prieta earthquake exhibited good performance (Botting and Buchanan, 2000). A review of sprinkler systems in hospitals affected by the Northridge earthquake (Fleming, 1998) revealed that 45% were undamaged. The value of 0.6 used here applies to systems complying with the current sprinkler standard (NZS 4514, 1996), taking into account the findings reported by Beattie (1999), but assumes that there are no special precautions taken to check and verify the design and installation of bracing to sprinkler pipework and suspended ceilings. The likelihood of the sprinkler system being damaged by poor performance of a suspended ceiling has been taken into account in this value.

The integrity of reinforced concrete or masonry water tanks (the most common materials) is likely to be high. In the period immediately following an earthquake (for the time it takes to evacuate the building, survey damage and review any threat of fire) it is assumed that sufficient water remains in a tank for sprinkler supply in 90% of buildings. In regions of highest seismicity (frequently occurring small earthquakes) diesel tanks and motors are likely to be provided with greater restraint than in areas where earthquakes are infrequent. Restrepo and Cowan (2000) report that frequently used diesel emergency generators worked well with exception after the damaging earthquake in Armenia, Colombia. Robertson and Mehaffey (1999) suggest that the reliability of a sprinkler system fed from on site storage designed to operate under the design level earthquake is in the range 60% to 80%. In a large earthquake in New Zealand, a 60% reliability is assumed here (i.e. that 40% of diesel pumpsets will not operate on demand immediately following an earthquake, for example due to damage to the motor or pump or fuel tank or pipe couplings).

Reviews of earthquake damage to infrastructure in urban areas (EQE, 1995; Borden, 1997; Restrepo and Cowan, 2000) has shown that a high proportion of town main water supplies are vulnerable to damage from liquefaction, ground slumping and settlement. However, this vulnerability is highly dependent on particular soil conditions. Significant water damage in buildings due to leaking or ruptured sprinkler pipework is also widely documented. Reports of extensive damage indicate that water supplies were available to these sprinkler systems immediately after the earthquake.

It is assumed that the probability of the sprinkler system being inoperable immediately after an earthquake because of loss of town main water supply to sprinklers is 0.80 and loss of a reticulated electricity supply for electric booster pumps is 0.90. The actual probability of not having a town water supply or electricity is arguably higher than this value, but experience with the systems used in New Zealand has shown that fires have been suppressed with the pressure and water contained in the sprinkler pipework alone (Marryatt, 1988) so slightly lower probabilities of loss of supply are assumed.

Given the crudeness with which input probabilities have been determined, the probabilistic assessment based on the above values can only give an indication of the order of magnitude of a structure being subjected to adverse fire exposure following an earthquake. Calculated values are summarised in Table 8.2.

Table 8.2 Estimated probability of adverse effect on structure resulting from fire following earthquake

outcome	Class A water supply	Class B or C water supply with electric booster pump	Class B or C water supply, no booster pump
2U structure adversely affected	9.5×10^{-5}	1.4×10^{-4}	1.2×10^{-4}
3F structure not adversely affected	4.1×10^{-5}	5.9×10^{-5}	5.3×10^{-5}
4F structure not adversely affected	6.4×10^{-5}	2.4×10^{-6}	2.4×10^{-5}
6U structure adversely affected	6.5×10^{-7}	2.4×10^{-8}	2.4×10^{-7}
7F structure not adversely affected	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}
total probability of adverse effect	9.5×10^{-5}	1.4×10^{-4}	1.2×10^{-4}

8.4 DISCUSSION

Interpretation of the probabilities determined from analysis of the event tree must recognise the gross assumptions made in evaluating input data.

The most significant effect is from the probability assigned to the likelihood of fire following earthquake for any given building. This reduces the likelihood of unsatisfactory structure performance to an order of magnitude less than the occurrence of the earthquake itself (Figure 8.2).

The probability is very low that the structure would be exposed to a fire that reaches flashover and could therefore adversely affect performance without passive fire protection. The absolute probability approaches that for the (more likely) case of fire in a sprinklered building (no earthquake). It is clearly much lower than the target minimum probability discussed in section 4.2.3 herein.

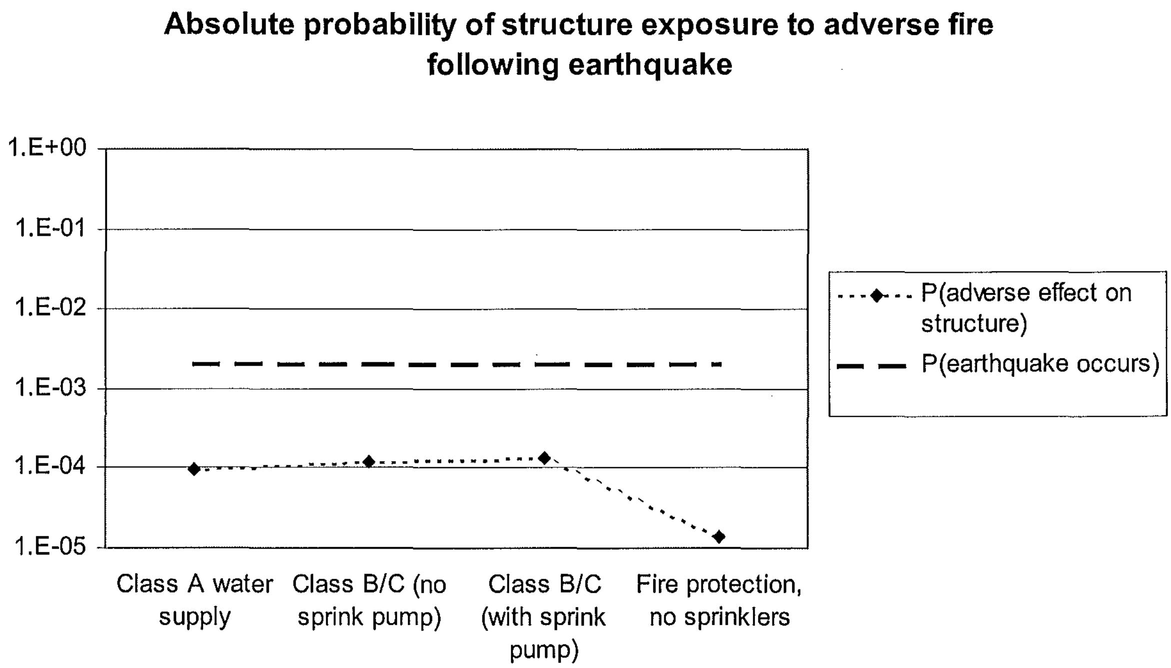


Figure 8.2 Probability of structure exposure to adverse fire conditions for fire following earthquake

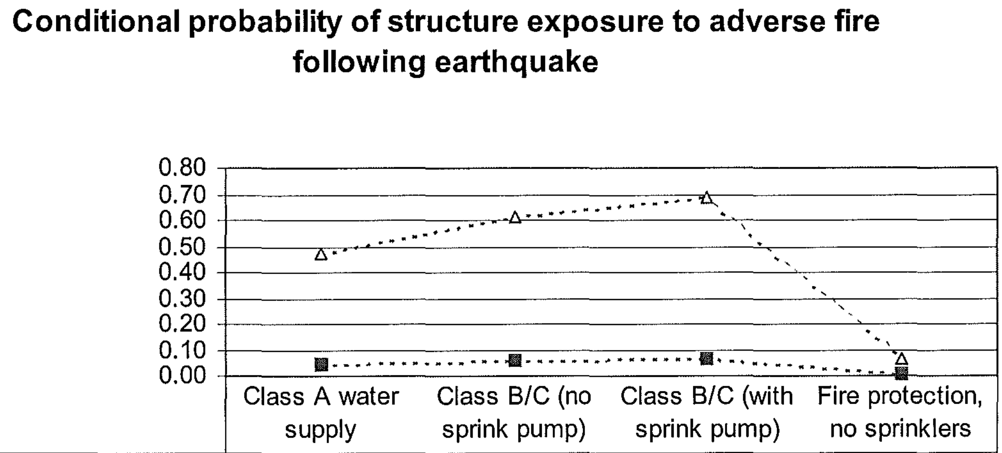
This low probability is largely a function of the low frequency of damaging earthquakes and the (assumed) relatively low probability for outbreak of fire following earthquake.

With such low absolute probabilities the influence of water supply class on sprinkler reliability is minimal. To gauge the significance of the different water supply scenarios, conditional probabilities are compared (Figure 8.3).

The graph illustrates two sets of values, compared in terms of conditional probabilities. The higher probabilities assume that an earthquake occurs and that a fire follows the occurrence of the earthquake i.e. that P(fire follows earthquake) = 1.0. The corresponding values show the variation of 'vulnerability' of sprinkler systems (hence structure) with different types of water supply if it is assumed that an earthquake occurs and fire starts as a consequence.

The second set of values (lower probabilities) indicate the probability of structure exposure to adverse fire assuming that an earthquake occurs and fire may or may not occur as a consequence. The value for the probability for fire occurring following an earthquake is as described in section 8.3.

This comparison removes the dominant influence of the low probability of fire following earthquake from masking these other trends. A sprinkler system which relies on either the water supply from the town main or the electricity supply is not particularly reliable in the scenario of fire following earthquake because there is a fairly high chance that one or both of these components will not be available immediately after an earthquake. Given that a fire follows an earthquake, the probability of adverse exposure of the structure to fire increases from less than 50% to 62% and 69% respectively for systems reliant on town main water supply and then also reliant on electricity for booster pumps.



	Class A water supply	Class B/C (no sprink pump)	Class B/C (with sprink pump)	Fire protection, no sprinklers
assuming earthquake occurs (fire may or may not occur as a result)	0.0476	0.0617	0.0692	0.0068
assuming a fire follows earthquake	0.476	0.617	0.692	0.068

Figure 8.3 Variation of probability of structure exposure to adverse fire for different water supply types

It is shown that applying passive fire protection applied to the structure is more effective in reducing the likelihood of adverse exposure to fire than relying on sprinklers in the case of a fire following earthquake. Of course this is not surprising, given the nature of earthquakes and the potential disruption to sprinkler systems and water supplies. The options considered relate to whether it is worth the additional expense of passive fire protection as well as the sprinkler system. For the more likely case of a fire occurring independently of an earthquake, there is no question that sprinklers are far more effective in achieving good structural performance than passive fire protection applied to the structure.

In the case of fire following earthquake, the additional benefit of applying fire protection is to reduce the already low probability that structure will be exposed to adverse fire conditions by roughly a factor of 5. Expressed another way, the average recurrence interval for structure exposure to adverse fire is increased from around 10,000 years to approximately 50,000 years for a case where the earthquake recurrence interval is of the order of 500 years.

Assuming that steel structures in seismic regions are designed in accordance with appropriate procedures, it is also important to remember that steel members and connections are able to withstand significant deformations and high ductility demands and still maintain adequate strength. (Feeney and Clifton, 1995; Hyland, 1999). The most important attributes relate to cross-section geometry (plate element slenderness) and connection detailing. Substantial experimental evidence exists to support these design and detailing recommendations (MacRae, 1990; Kasai and Popov, 1986; Clifton and Butterworth, 1998). Therefore the structures which are subjected to significant seismic loads can also accommodate a significant amount of load redistribution and withstand relatively severe local buckling. These features are important to withstand the effects of exposure to the high temperatures in a fire, so if a structure is constructed without passive fire protection it has a greater capability to withstand exposure to flashover fire conditions if it is also designed to withstand seismic load ductility demands.

8.5 SUMMARY – FIRE FOLLOWING EARTHQUAKE

It is clear that more information is needed on the frequency and type of fire start and fire damage in buildings as a result of earthquakes. This information will establish the fundamental degree of risk involved. Consequences of failure of fire systems varies with different occupancy and building types, but this has not been included in this assessment of the impact of fire following earthquake on structure performance.

Regardless of assumptions made in this risk assessment, the probability of a steel structure not performing adequately as a result of an outbreak of fire following an earthquake can never be higher than the probability of the earthquake occurring. Even if it is assumed that an earthquake will definitely occur the annual probability that the structure would be exposed to adverse fire conditions is expected to be less than 5% if a class A water supply is provided.

Given the very low probability that a steel structure without passive fire protection would be exposed to adverse fire conditions, it is suggested that no special design precautions are needed to mitigate this risk. Exposure to adverse fire conditions (e.g. flashover) does not necessarily mean that the structure performance will be unsatisfactory. This issue is discussed in more detail in section 9.

However, for wind and seismic forces, exposure of the structure to the threat does not mean that structural failure will occur. To be consistent, collapse of the structure must still be avoided even though the risk of exposure to adverse fire conditions is very low.

Design procedures and recommendations exist (Clifton, 2000), although presently still in draft form, which allow verification of structural adequacy at elevated fire temperatures. These typically involve applying passive fire protection to steel columns.

In buildings or occupancies where there is an acknowledged greater risk of a fire start following an earthquake and the performance of the structure might affect the end result, measures should be taken to minimise or move the threat, or to re-examine the risk to structure more thoroughly. This may involve a more detailed assessment of the performance of the structure to withstand fully developed fire conditions. However, if life safety is the main concern, then as usual it is the threat of smoke spread in an occupied building that will be the most serious fire threat (either to other spaces on the same floor or between floors).

Alternatively, where fire following an earthquake is regarded as a serious threat in a sprinklered building, effort should be devoted to constructing a more robust sprinkler system, ahead of adding cost by applying passive fire protection to protect the structure. Assuming that an on-site sprinkler water tank and diesel pumpset is provided (as required by the sprinkler standard for buildings higher than 25 metres in areas of moderate to high seismicity), one option is to have the design and installation of the seismic restraints to sprinkler pipework and pumps independently reviewed and certified. Cost-benefit considerations will apply.

In the event of a fire following an earthquake, an operable sprinkler system would control fire spread, thus protecting building occupants, limiting fire damage, preventing spread of fire to neighbouring building and protecting the structure from fire exposure Passive fire protection only addresses the last of these capabilities.

9 PERFORMANCE OF STEEL STRUCTURES IN FULLY DEVELOPED FIRES

9.1 FACTORS AFFECTING STRUCTURAL RESPONSE TO FIRE

Many factors determine the effect of fire on a steel structure. In general terms these can be classified as

- factors which affect fire growth and fire size
- factors which influence exposure of the steel structure to fire and consequently the temperatures experienced by the steel members
- factors which determine the physical and mechanical response of the steel members and connections to these elevated temperatures

The most important influence is the fire itself – its size and intensity, duration and location. All of the factors which affect fire start, fire growth to full development and fire intensity and duration in the fully-developed phase therefore indirectly influence the response of the structure. The dominant aspects of fire behaviour are the amount and arrangement of fire load and ventilation, enclosure size and the presence of automatic detection and suppression systems.

Other factors which affect the likelihood of a damaging fire include the presence of ignition sources, number and location of occupants and their pre-fire state, availability of fire service and first aid fire-fighting equipment.

The effect of the fire on temperatures of members in a steel structure depends on features of the structure, such as the size and shape of the steel sections, the location of the steel members relative to the fire and in relation to the enclosure itself, the presence of barriers or coatings that interfere with the radiant heat flux received by the steel members.

The response of the steel structure to the elevated temperatures is a function of

- the type of structural system

- its redundancy and ability to withstand ductility demand
- its interconnection with other structural elements (such as concrete slabs or walls)
- the loads supported by the structure at the time of the fire
- the end connection details
- the ability of members and connections to withstand thermally induced deformations and to redistribute loads to other parts of the structure
- the high temperature creep characteristics of the steel.

In a full risk assessment, all of these factors play a part in assessing the probability of inadequate structural performance in fire. Many are dependent on the occupancy type or the features specific to a particular building under consideration. Therefore, any general risk-based framework for structural fire design needs to incorporate this wide range of design variables and must make a number of conservative assumptions in order to obtain a result that can be applied generally.

That is why the approach in this report has not attempted to cover the range of structural designs and response that are possible. These can only be addressed properly on a case by case basis. In general, a more specific approach would result in a less conservative design than would be obtained using the results of this research.

9.2 FIRE RESISTANCE AND PASSIVE FIRE PROTECTION

9.2.1 The Need for Fire Resistance

Traditionally, the specification of passive fire protection to steel structures has arisen from the need to satisfy prescriptive codes for fire safety. However, these requirements were not based on a detailed knowledge of natural fire behaviour or an understanding of the actual performance of steel structures in fire. They arose from a well-intended desire to minimise damage to the structure, in order to reduce overall fire loss or cost of structure replacement.

The performance of passive fire protection materials is measured by the results of a standard fire test (ISO 834, 1975). This test procedure is intended to represent the temperatures experienced if the element of construction was exposed to a fully developed fire.

While there may have been some recognition of the characteristics of real fires in determining the test details, the conditions of the standard fire test are not closely related to real fire situations. The rate of temperature increase as a function of time is related more to the capabilities of the furnace control systems than to simulating a real fire. Also, the temperature continues to increase with time and there are no limits reached in terms of quantity of fuel consumed, fire size, heat output, burning rate, or ventilation limit. These departures from real fire performance combine to produce a test method which cannot be regarded as representative of real fire conditions. Consequently, fire resistance as measured by the standard fire test is useful as a means of assessing relative performance of elements of construction but is limited as a tool for predicting performance of elements of construction in a real fire.

The history of prescriptive specification means that passive fire protection requirements are almost always assumed to be necessary and have been specified without really knowing whether they are either sufficient, or necessary, to achieve a certain level of performance in real fires.

Attention is now focussed on the performance of steel framed buildings in fire as a result of the world-wide trend towards performance-based fire safety design (Eurofer, 1990; Thomas, 1996; Bennetts et al, 1996; Feeney, 1998). Engineers now better understand the actual behaviour of steel structures in natural fires and the requirements necessary to achieve a certain fire resistance. More specifically, the need for passive fire protection of steel structures can be critically reviewed to determine if in fact such requirements are necessary to achieve a specified performance in fire.

9.2.2 The Need for Passive Fire Protection

In this report the assumption has been made that if a fire large enough to activate sprinklers is not controlled by the sprinkler system it grows to a size and severity that can threaten structural stability. However, not all cases of fire reaching flashover conditions result in structural instability if the steel members are not insulated with passive fire protection (Lawson, 1991; Thomas, 1992a; Feeney, 1998). Structure performance is dependent on the fire severity and the inherent fire resistance of the unprotected steel members. Therefore, in many cases this is a very conservative assumption.

Because steel begins to lose strength and stiffness when it is heated above around 200°C, passive fire protection has historically been applied to structural members to insulate them from the effects of fire, so they can continue to support loads during a fire with similar performance to that expected at room temperature. However, this is effectively all that passive fire protection achieves. It does not directly contribute towards meeting other fire safety performance objectives. For most buildings, insulating the structural frame to prevent collapse during a fire is the least effective way of reducing loss of life or financial loss from fire damage. If the temperatures in an enclosure on fire reach the level at which an unprotected steel structure is in danger of collapse, then most of the costs (life safety and property damage) associated with a fully developed fire in at least one firecell in the building have already been incurred.

There are many examples of disastrous fires such as those at First Interstate Bank building (Gregerson, 1989; Nelson, 1989) and Dusseldorf airport (Wolf, 1996), where other important fire protection objectives (such as preventing loss of life or controlling substantial property damage) have not been met, even though passive fire protection was applied to the structure and performed as required. A functioning sprinkler system was not provided in either of these cases.

Robinson (1995) noted the irony of the prescriptive 'fire protection' approach (compared with structural design for other load effects) and argues for an engineered solution to provide adequate performance of steel structures in fire. Incorporating the direct contribution to fire safety from other installed systems such as sprinklers is a logical part of this more rational design approach.

9.2.3 Reliability of Passive Fire Protection

One of the more common forms of passive fire protection applied to steel structure is sprayed insulation using mineral fibre or vermiculite-based materials. This is applied to the structure to a specified thickness, depending on the size of the steel section being protected and usually before building services are installed. Very little is published about the reliability of this form of fire protection. It is usually assumed to be 100% reliable over the life of the building because it requires no on-going maintenance.

Provided the material is installed correctly this assumption would be close to the actual situation, except that it is often dislodged locally when work is carried out on ceiling void services. There is therefore a finite probability that the passive fire protection will not provide the protection expected.

FCRC (1996) gives a value of 0.95 for the probability that a barrier providing fire resistance will perform as intended. Similarly, DD240 (1997) suggests a probability of 0.05 that passive systems providing fire compartmentation may be perforated (before fire start) and therefore not perform as required. This perforation is likely to result from building services alterations, the same cause of damage to passive fire protection to steelwork. To account for the possibility that the material is not installed to the correct thickness or, more likely, that it is not applied to all of the required members, this value seems reasonable. Passive fire protection 'failure' is more forgiving than sprinkler failure in that its effect on the structure is very localised and is unlikely to affect overall structural performance. Conversely, sprinkler systems have the advantage of being inspected and maintained at monthly intervals throughout the life of the system, so arguably the sprinkler systems are more reliable as a building ages and is subjected to extensive internal alterations.

9.3 EXPERIMENTAL RESULTS

It has been known for some time (Newman et al, 2000; Modern Steel Construction, 1998) that beams and columns in a steel framework subjected to fire conditions behave much better than an isolated member subjected to the standard fire test. This is related to differences between the conditions imposed by the standard test to maintain uniformity and the interaction with other members in a frame. To evaluate the significance of these differences and also the performance when subjected to natural fires (not the standard heating curve of the fire test), a number of full scale tests on steel structures exposed to natural fires have been conducted in recent years. The most significant of these are reported by Thomas et al (1992a), Proe and Bennetts (1994), Clifton (1998) and Bailey et al (1999).

The results of these full scale experimental tests utilising unprotected steel beams acting compositely with a concrete slab have confirmed the generally satisfactory behaviour of such systems when exposed to real fires. The important outcomes from the experimental tests are summarised by Clifton (1998). Aspects of performance relevant to this study are re-stated below:

- There has been no local or global collapse in any of the structural systems tested.
- There has been no loss of integrity of any floor system tested
- The experimental tests involved fire loads of 40 to 65 kg/m^2 wood equivalent. This ranges from the 80% fractile for fire load in an office occupancy to the maximum credible fire load.
- The structural fire severity of the tests was representative of or more severe than that expected for real fires. Peak air temperatures of more than 1150°C and peak steel temperatures above 1100°C were developed in some tests. These temperatures were much higher than theoretical calculated limiting temperatures.
- During the heating phase, beams experienced large downwards deflections, with rotation occurring at end connections. Local buckling of bottom flanges and diagonal buckling in the web occurred in some beams at the end supports, with considerable permanent distortion of the floor slab and supporting beams.
- As beams shortened during the cooling phase, the tension force that developed on end connections fractured some bolts and induced cracking in flexible endplates in some connections.
- For tests in which there has not been any form of suspended ceiling, considerable permanent distortion of the floor system has occurred. For the tests which did incorporate a standard (non fire rated) suspended ceiling, little permanent distortion of the floor system occurred.
- The tests showed that passive fire protection to the floor support beams is not necessary to prevent collapse or loss of integrity, but it does suppress deflection and distortion of the steel beams.

Results from experimental full scale tests representing fires in specialty shops in shopping centres (Bennetts et al, 1998) also demonstrated adequate performance from unprotected steel beams subjected to intense fires (fire temperature up to 1320°C and steel temperature up to 1250°C).

While the test results clearly demonstrate that satisfactory performance can be achieved from unprotected steel structure exposed to severe fires, it is important to understand and appreciate the limit of application of conclusions drawn.

All tests were conducted with passive protection to the steel columns, so the same acceptable performance does not necessarily apply to frames with unprotected steel columns exposed to the similar fire conditions.

Local buckling occurred in the beams near their supports. If the behaviour of unprotected steel when exposed to severe fires, as described above, is to be relied on in steel frames, then a check of the steel beam section geometry and section ductility is required to confirm that the beam sections can withstand this ductility demand without failure.

Some cracking and bolt failures occurred in the connections due to the pull-in forces experienced as the beams cooled. Although there was no loss of structural stability or integrity in the tests, this failure mode should be suppressed. A check of the connection design philosophy and detailing is required to ensure that this potential failure mode has been addressed. Guidance on steel connection design to cater for seismic-induced ductility demand on connections (Feeney and Clifton, 1995; Hyland, 1999) is expected to adequately cover this type of demand on connections.

Also, there are other structural load-carrying mechanisms, such as tensile membrane action in the floor slab (Wang, 1996; Rose, 1998), that help to achieve the good behaviour observed in the experimental tests mentioned above. If it is anticipated that the structural system would be subjected to severe fire conditions and expected to respond as observed above, then attention must also be paid to these detailing requirements.

9.4 PERFORMANCE IN ACTUAL FIRES

The *limiting* temperature T_l , defined in the New Zealand Steel Structures Standard NZS 3404 (1997) can be regarded as the temperature of the steel member beyond which it may not reliably support the imposed structural design load likely to be present at the time of a fire (specified in the Loadings Standard NZS 4203:1992). This is a conservative definition because the limiting temperatures are based on conservative methods for assessing performance in a real fire. Calculated limiting temperatures are typically more than around 550°C, so for all practical purposes only those fires which grow to flashover and full development are likely to have an effect on the strength and stability of an exposed steel structure. This can only happen if the outbreak of fire is not controlled by the automatic sprinkler system.

The attainment of the steel *limiting* temperature represents a threshold in the expected performance of a steel beam to withstand a fire without significant permanent damage, but does not mean that either the structure or the individual members will collapse. The extent of reserve capacity in the member or structure depends on the degree of redundancy and the ability of the structure to redistribute loads or to support loads using alternative structural mechanisms (that are usually ignored in routine design).

This load-sharing due to continuity and redundancy is important because it allows individual elements in the structure to be heated beyond their *limiting* temperature without affecting the structure's overall strength and stability. This also accounts for the substantially better performance of real multi-storey steel structures in actual fires that is observed in practice compared with what would be expected from the results of standard fire tests on individual members.

Clifton and Forrest (1996) and Thomas et al (1992a) summarise details of more than twenty cases of actual fully developed fires in multi-storey steel framed buildings. Important features of the steel frame behaviour in these cases were:

- No noticeable distortion of the frame was reported in the majority of cases (most of which involved passive fire protection of the structural members but included structures with unprotected steel members)
- No cases of global or local collapse were reported, even in the structures with unprotected steel beam and/or column members.
- Some distortion of unprotected members was reported. In one instance where most of the structural members were unprotected, considerable distortion of the floor

system and some column members occurred, but without loss of stability or integrity of floors acting as fire separations between levels.

- Localised shear failure of bolts in simple beam web side plate connections occurred in a few cases. These involved beams which were unprotected or had lost passive protection over part of their length. However, this bolt failure had no detrimental effect on the overall structural system performance.

- The frames acted as a complete structural entity in each case, rather than as a series of individual elements. In some cases, where all of the members were unprotected, this produced a significant increase in a structure's resistance to failure over that obtained under standard fire test conditions e.g. as calculated in accordance with NZS 3404 (1997).

A summary of reports of fatal fires in high-rise buildings and significant fires in high-rise office buildings that have occurred internationally since 1970 has been collated by Thomas et al (1992b). These cover 34 fires in a variety of building types. It is notable that in all cases reviewed the building structure withstood the fire without significant, and in some cases, any, damage to the structure, regardless of the number of people killed in the fires. Structural damage to beams, floor slabs and columns, where reported, was generally minor. In two cases where there was some structural damage, apparently this was only to the floor system directly above the floor of fire origin.

Factors in the design and construction of the buildings which may have contributed to the deaths include the lack of automatic sprinkler systems. None of the buildings had a functioning sprinkler system on the storey of fire origin or in the other storeys involved in the fire. And yet none of the buildings suffered significant structural damage.

Not surprisingly, a large proportion of the fatalities resulted from smoke inhalation. Others were killed either jumping or falling from the buildings, but at the time most were being severely threatened by flames or smoke. It is clear from the reviews that the performance of the structure in fire, whether or not it was as intended, had no adverse effect on life safety in these fires.

One of the best documented real fires in a building with unprotected structural steel was the 1990 Broadgate Phase 8 building in London (Lawson, 1991). Unusual circumstances resulted in unprotected steel columns and floor support structure at the first floor of a 14 storey building being subjected to a severe fire of relatively long duration. Considerable localised member and floor slab distortion occurred but there was no loss of structural stability or integrity. Columns suffered severe local buckling due to axial restraint of thermally-induced compression forces. However, the damaged structure was still able to support the design 'long term' load applied during subsequent load testing.

Damage to steel structures in fire following earthquake is also reported in Park et al (1995) from observations in Kobe, Japan. Most of these were low-rise buildings. Older framed buildings with light truss beams and small section columns were often badly damaged by fire, with collapse of roof support structure and severe sagging of upper floor support trusses. This form of construction is more typical of light industrial or residential structures in New Zealand and exhibited failures that would also be expected here if subjected to a severe fire.

The structure in modern buildings, with I-section or hollow section columns and I-section steel beams supporting concrete floor slabs on metal decking, suffered little effect from fire, with some permanent deflection of floor beams but no loss of structural integrity or stability noted.

9.5 RESULTS OF ANALYTICAL MODELLING

For most situations, analytical modelling to predict behaviour of unprotected steel structures when subjected to fully developed fire is limited to methods based on empirical relationships or parametric studies. Beyond the simplistic elemental analysis, the problem becomes very complex and computationally demanding. The use of complex analytical modelling to predict the behaviour of unprotected steel members in fire is restricted indirectly by the understanding and acceptance of alternative designs by regulatory authorities. An overview of the range of analytical design methods and their acceptance in various countries is provided in Eurofer (1990) and IISI (1993).

In New Zealand most design of unprotected steel members in fire is carried out in accordance with the method in the Steel Structures Standard NZS 3404 (1997) and the Acceptable Solutions for Fire Safety (BIA, 1995), with reference to the Loadings Standard NZS 4203 (1992). This method calculates a period of structural adequacy for the various steel components that make up the structure, assessing performance during fire in terms of the limiting steel temperature. This method is convenient for analytical modelling because it enables a direct correlation to be made using various analytical methods e.g. between structural analysis/design and fire modelling/thermal analysis. However, it is inherently conservative because the approach relies on analysis and design procedures which simplify the problem so it is amenable to calculation.

However, even the relative simple methods can be extended to more accurately reflect behaviour of members in full frames subjected to natural fires. Design is also carried out using the equations for the parametric time-temperature curve contained in ENV 1991-2-2 (1995). This gives a better indication of how a member in a structure might behave if subjected to a natural fire (as distinct from the prescribed heating curve for the standard fire test). This procedure has been adopted for many building structures and confirms that exposed steel structures can withstand the effects of a severe fire (reaching full development) without steel temperatures exceeding their limiting values (Feeney, 1998). Unfortunately, the range of design scenarios where this procedure gives useful results is limited.

More sophisticated methods for calculating the response of steel frames to fully developed fire conditions are published in draft form (Clifton, 2000) and are still under development. Although this design procedure for inelastic floor system and frame response is intended to be used in the design office, its complexity limits its application to some larger scale projects only.

The results of finite element analysis (Moss and Clifton, 1999) of an existing 17 storey office building subjected to a range of natural fires of varying severities also predict stable behaviour from unprotected steel beams and elastic response from the protected steel columns. Even under the action of a nominal simultaneous horizontal wind load, horizontal deflections of the building remain small, confirming that the lateral stability of the building is not adversely affected by the fire. Not surprisingly, the sophisticated analytical methods used in that research are not suitable for design office use.

The results from both of these analytical methods demonstrate that in many cases unprotected steel structure can withstand exposure to fully developed fires and still meet the performance requirements of the New Zealand Building Code. It is therefore quite conservative to assume, as in this report, that steel structure would be adversely affected when exposed to fully developed fire conditions.

9.6 NECESSARY ATTRIBUTES TO ENSURE STABILITY OF STEEL FRAMES IN FULLY DEVELOPED FIRES

The following attributes are considered necessary for unprotected steel frames if they are to perform in a similar way to those structures described in this section of the report, when subjected to a fully developed fire. In this context, the following attributes must be regarded as essential but are not necessarily a complete list of requirements for compliance with all New Zealand Building Code performance objectives.

- A concrete floor slab or concrete topping slab designed as a structural diaphragm is provided at each floor level, interconnecting lateral load resisting frames and gravity load resisting frames

- Steel beams must act compositely with a concrete floor slab at least to the extent that the floor slab provides full lateral restraint to the steel beam critical flanges. Some form of mechanical anchorage between the beam top flange and the concrete topping slab is assumed to be present (friction alone is not sufficient even though it may provide full lateral restraint to the steel beam).

- The mechanical anchorages providing the shear connection between the steel beam and the top slab must be capable of achieving the required ductility associated with the large downward deflections likely to be experienced by the beams.

- Plate element slenderness of the beam bottom flange and beam web are to be compact (complying with section geometry requirements for category 2 members in seismic design).

- Beam end connections to be designed and detailed to provide a high degree of ductility and rotational capacity, paying particular attention to avoidance of non-ductile failure modes in welds and bolts.

- Steel element thickness and material properties are to be within the scope of the Steel Structures Standard NZS 3404

- Steel columns are to be protected from exposure to high temperatures that would cause additional thermally induced axial forces, local buckling, member buckling or large high temperature creep strains.

- Where large deformations of the floor slab are expected and relied on to support gravity loads during a fire, ductile reinforcing mesh or bars are to be provided in the topping slab. Additional longitudinal reinforcement is to be placed adjacent and parallel to the primary beams to provide enhanced negative moment capacity over the primary beam supports, as required. Any additional longitudinal reinforcement placed along secondary beams is to be anchored around the external face of supporting columns. Specific advice on suitable design and detailing provisions are described by Clifton (2000).

More research and analysis is needed before suggestions can be given for frames in which the steel columns are constructed without fire protection and are exposed to fire.

Some of these attributes are needed to a lesser extent depending on the likelihood and severity of expected fire conditions. For example, car fires in open carpark buildings typically present a less severe threat to the structure than a fire in an office building. A thorough knowledge of the effect on structural behaviour of the features provided, is required to assess the extent to which individual requirements can be reduced in specific cases.

10 LIKELY PERFORMANCE OF STEEL STRUCTURE IN SPRINKLERED BUILDINGS

10.1 RISK ASSESSMENT

For the purposes of this risk assessment the following terms are defined:

T2 fire = fire large enough to activate a sprinkler system (if present)

A = the set of sprinklered buildings

B = the set of unsprinklered buildings

S = the set of T2 fires occurring in sprinklered buildings, and

$N[S]$ = number of T2 fires occurring in sprinklered buildings/year (average rate of occurrence)

T = the set of T2 fires occurring in unsprinklered buildings, and

$N[T]$ = number of T2 fires occurring in unsprinklered buildings/year

X = the set of uncontrolled fires in sprinklered buildings, and

$N[X]$ = number of uncontrolled fires in sprinklered buildings/year

Y = the set of uncontrolled fires in unsprinklered buildings, and

$N[Y]$ = number of uncontrolled fires in unsprinklered buildings/year, on average

$P[X]$ = probability of an uncontrolled fire occurring in a sprinklered building

The sample space considered by Marryatt (1988) is the set S, representing 'type T2' fires in sprinklered buildings. This is a subset wholly contained within the larger set A of all sprinklered buildings. The subset X of uncontrolled fires in sprinklered buildings is contained wholly within the set S of 'type T2' fires in sprinklered buildings, since it is assumed that all uncontrolled fires will be large enough to activate the sprinkler system.

Using the above terms the following probabilities are constructed:

The probability of a T2 fire occurring in sprinklered building

$$P[T2\,fire/sprinklered\,building] = \frac{N[S]}{N[A]}$$

The probability of this fire becoming uncontrolled, given the occurrence of a T2 fire

$$P[\mathit{fire\,uncontrolled}/T2\ \mathit{fire}] = \frac{N[X]}{N[S]}.$$

Values for this statistic are commonly quoted from Marryatt's study (1988). While they indicate the reliability of sprinklers they are not a measure of the probability of an uncontrolled fire occurring in a sprinklered building.

The annual probability of an uncontrolled fire occurring in a sprinklered building

$$P[\mathit{fire\,uncontrolled}/\mathit{sprinklered\ building}]$$

$$= P[T2\ \mathit{fire\ in\ sprinklered\ building}] \cdot P[\mathit{fire\ uncontrolled}/T2\ \mathit{fire}]$$

$$= \frac{N[S]}{N[A]} \cdot \frac{N[X]}{N[S]}$$

$$= \frac{N[X]}{N[A]}$$

where $N[X]$, $N[S]$ and $N[A]$ are assessed on a yearly basis. An effect of this simplification is to overlook the assumption that the historical rate of fire starts in sprinklered buildings $N[S]/N[A]$ will remain roughly the same in the future. If $N[S]$ increases but the sprinkler effectiveness, measured by $N[X]/N[S]$ remains constant, then both $N[X]$ and the probability of uncontrolled fire increases. In the past, the requirement for installing sprinkler systems has been driven strongly by the former prescriptive fire codes. They were provided in the specific risk occupancies such as hospitals, high rise buildings, etc. Now that sprinklers are being installed more frequently into occupancies where they are chosen for 'cost' reasons not just fire safety reasons, the exemplary performance to date may not continue, because they are being used in a wider range of occupancies; including those in which the probability of fire starting/spreading may be greater than historically.

Much of the data used to quantify the above probabilities is available from Marryatt (1988). It is assumed that the events in set X, the occurrence of an uncontrolled fire in a sprinklered building, are random and can occur in any sprinklered building.

In the 100 year period from which data on fires was analysed (Marryatt, 1988), the outcomes reported include the occurrence of fires which are 'controlled' and which are 'not controlled', mutually exclusive events. These outcomes measure the likelihood of all events in the following sequence:

- the probability of a fire occurring in a sprinkler-protected building
- the probability of the fire growing to the size that activates at least one sprinkler head
- the probability that the sprinkler head(s) activate as intended
- the probability that the fire is controlled or suppressed

Incorporated in this last event is the probability that a suitable supply of water is available to control or suppress the fire.

For sprinkler operation in New Zealand, $N[X] = 2$ for the 113 year period 1886 to 1999 (0.018 per year) and $N[A]$ is estimated to be 2700 on average over this time (half of the current estimate of 5400 sprinkler valvesets - see sections 5.1.2 and 6.3.3 herein).

Therefore, the annual probability of occurrence of an uncontrolled fire in a sprinklered building in New Zealand, using the data recorded by Marryatt,

$$\begin{aligned} P[fire\,uncontrolled / sprinklered\ building] &= \frac{N[X]}{N[A]} \\ &= \frac{0.018}{2700} \\ &= 6.6 \times 10^{-6} \end{aligned}$$

For sprinkler operation in Australia, $N[X] = 45$ for the 100 year period 1886 to 1986 (0.45 per year) and $N[A]$ is estimated to be 15,000 on average over this time - half of the current estimate (T. Williams, pers. comm.) of 30,000 sprinkler valvesets.

Therefore, the annual probability of occurrence of an uncontrolled fire in a sprinklered building in Australia, using data recorded by Marryatt,

$$\begin{aligned} P[fire\,uncontrolled / sprinklered\ building] &= \frac{N[X]}{N[A]} \\ &= \frac{0.45}{15000} \\ &= 3.0 \times 10^{-5} \end{aligned}$$

In assessing a course of action for a future building, when the decision to include sprinklers or not has not been made, it would appear that the assessment of probability of a type T2 fire occurring should also incorporate probabilities relevant to unsprinklered buildings so that

$$P[T2\,fire] = \frac{N[S]+N[T]}{N[A]+N[B]}$$

However, as soon as the effect of incorporating sprinklers is being considered, it is appropriate only to account for the conditional probability assuming the building is sprinklered because this becomes the only relevant set of events if sprinklers are chosen to be installed.

Using the data collated in this report, the annual probability of a fire occurring in a sprinklered building severe enough to threaten a steel structure can also be assessed independently from Marryatt's results.

The events and associated probabilities can be depicted in the form of an event tree and incorporated into a risk assessment model. They are described in Table 10.1.

By inspection of the event tree, the probability of a fire occurring in a sprinklered building in New Zealand that is capable of growing to a size that threatens structural stability is the product of 0.2 x 0.033/year = 6.6 x 10^{-3}.

For the favourable outcome (denoted *F*) where the fire does not reach full development, the outcome of all three contributing events must also be favourable (water supply available, sprinkler system available, sprinklers effective). The probability of the unfavourable outcome (denoted *U*) – fire reaches full development (given an outbreak of fire which then spreads beyond the object of initial involvement) – is given by

$$\begin{aligned} U &= 1 - P[F] \\ &= 1 - (0.99992 \times 0.9984 \times 0.9982) \\ &= 1 - 0.9965 \\ &= 0.0035 \end{aligned}$$

Table 10.1 Probabilities for independent event tree analysis

independent event	conditional probability of occurrence
Outbreak of fire in a sprinklered building	0.033 / year
Spread of fire (mutually exclusive events)	
Fire spreads beyond the object of initial involvement, activates sprinkler and, if not suppressed, is capable of growing to a size that threatens structural stability	0.20
Fire does not spread beyond object of initial involvement regardless of sprinkler operation; extinguished by occupants or fire service or self extinguishes	0.80
Water supply availability (mutually exclusive events)	
unavailable at required pressure and flowrate	0.00008
suitable supply available	0.99992
Sprinkler system shutdown (mutually exclusive events)	
isolated for alteration or maintenance	0.0016
sprinkler system fully functional	0.9984
Sprinkler system activates (mutually exclusive events)	
sprinklers not effective in controlling fire	0.0018
sprinklers effective in controlling fire [a] (hence fire does not reach full development)	0.9982
Fire reaches full development (mutually exclusive events)	
structure becomes unstable due to fire exposure	1.0 (assumed)
structure does not become unstable due to fire exposure	0.0 (assumed)

Note:

a. Sprinkler effectiveness is taken as ratio of 1 - (uncontrolled fires /total fires) = 1 - (4/2201) for New Zealand for the period 1886 to 1999 (see section 6.3.3).

The probability of a fire in a sprinklered building New Zealand growing to a size that threatens structural stability is therefore the product of the unfavourable outcome relating to sprinkler operation, U, and the probability that the fire is capable of reaching full development. That is, the annual probability of occurrence of an uncontrolled fire in a sprinklered building is

$$\begin{aligned} P[\textit{fire uncontrolled}/\textit{sprinklered building}] &= 0.0066 \times 0.0035 \\ &= 2.3 \times 10^{-5} \end{aligned}$$

This is higher than the same probability assessed using Marryatt's data, (6.6×10^{-6} as given previously in this section) which is not surprising for the following reasons:

- The probability of fire start in sprinklered buildings used in this alternative assessment does not differentiate between different occupancy types, so it includes all sprinklered buildings, not just those which are within the scope of this study.

- Because the value for sprinkler effectiveness is based on actual fire occurrences it already takes into account the likelihood of the water supply or the sprinkler system not being available at the time of the fire, so these influences have been included twice. Removing this potential double-up might reduce the probability to 1.2×10^{-5}.

- It is a theoretical probability, whereas the value assessed from Marryatt's data measures the actual probability of occurrence.

The probability based on Marryatt is likely to slightly underestimate the true probability for the following reasons:

- The actual average number of sprinklers installed over the sample period (113 years) was likely to be less than that used to calculate the probability.

- The frequency of uncontrolled fires is likely to be greater than that assessed using historical data because of the increase in numbers of sprinklered buildings. This would occur even if the reliability of sprinklers remains constant. With such a small number of occurrences, an increase in the sample by only one fire significantly affects the calculated probabilities.

The actual probability is expected to be somewhere between these two assessed values. The outcome selected for this report is that the annual probability of occurrence of an uncontrolled fire in a sprinklered building in New Zealand is estimated to be 1.2×10^{-5}.

10.2 THE PROBABILITY OF UNACCEPTABLE STRUCTURAL PERFORMANCE IN FIRE

In this report the assumption has been made that if a fire large enough to activate sprinklers is not controlled by the sprinkler system it will grow to a size and severity that can threaten structural stability. This significantly overestimates the number of fires that might threaten steel structures, so in that respect is a very conservative assumption. It has been made because it avoids the need to specifically assess the ability of the steel structure to perform adequately under fully developed fire conditions – a necessary simplification to be able to derive generally applicable conclusions. In the data in Table 10.1 for the event tree analysis described in that section, the probability that the structure becomes unstable due to exposure to fully developed fire is taken as 1.0. From the discussion in sections 9.1, 9.3 and 9.4 it is clear that there are many factors that determine the structural response to fire and it is by no means certain that the stability of steel members would be threatened in any particular case involving exposure to fully developed fire. The resulting probability that a structure becomes unstable is therefore overestimated.

Based on the results of this research, the probability of the steel structure being subjected to fire conditions which are capable of producing a structural response that does not satisfy the performance requirements of the Building Code is less than 1.2×10^{-5}. This low probability is mainly due to the high effectiveness of sprinkler systems to control fire growth to a size that does not affect the performance of the structure. This assessment does not assume or require that passive fire protection be applied to the structure.

Table 10.2 Approximate probability of structure being exposed to adverse fire conditions

Sprinklered building; no earthquake	1.2×10^{-5}
Sprinklered building; fire following earthquake; Class A water supply	9.5×10^{-5}
Sprinklered building; fire following earthquake; Class B or C water supply, no booster pump	1.2×10^{-4}

Even with the assumption that fully developed fires could/would result in structural instability from fire, the approximate probabilities given in Table 10.3 are very much lower than the target annual probability of failure of 2.0 x10^{-3} from section 4.2.3. The probabilities associated with fire following earthquake are not much higher than for the case with no earthquake (within an order of magnitude). This suggests that the risk associated with fire following earthquake is significantly less than is commonly assumed.

It is interesting to compare these failure probabilities with other low probability events and risks (Table 10.3).

Table 10.3 Comparison of probability of fire reaching flashover in a sprinklered building in New Zealand with other low probability events

event	approximate annual probability of occurrence
steel structure in a sprinklered building in New Zealand being exposed to a fire which reaches flashover	1.2 x10^{-5} or less
steel structure in a sprinklered building in New Zealand being exposed to a fire which reaches flashover soon after an earthquake, assuming a severe earthquake has occurred Class B or C water supply, no booster pump	1.2 x10^{-4} or less
winning 1st division prize in Lotto public lottery with the purchase of one ticket each week for 12 weeks (prize pool approx. $NZ 1.3 million)	1.25 x 10^{-5}
estimate of annual probability of tsunami between 5 and 10 metres high occurring in the Wellington region	approx. 1.2 x 10^{-2}
estimated likelihood of collision between planet Earth and comet or asteroid, sufficient to threaten global civilisation (Verschuur, 1996)	approx. 1.0 x 10^{-4}

10.3 ACCOUNTING FOR THE VALUE OF SPRINKLER PROTECTION

It is clear there is a significant difference in the probability of a steel structure being exposed to adverse fire conditions that might affects its stability and the target exceedance probability for other ultimate limit state events for structural design. The probability of adverse fire exposure for the typical case is more than 150 times less likely than exposure to other ultimate limit state events for structural design (comparing probability 1.2 $\times 10^{-5}$ with the general structural target probability of 2.0 $\times 10^{-3}$).

A review of the current state of design and knowledge concerning the response of steel structures to fully developed natural fire conditions has shown that adverse fire exposure typically does not lead to structural instability or collapse.

Based on the low probability of the structure in a sprinklered building not satisfying the Building Code performance requirements, it is suggested that the application of passive fire protection to certain types of steel structures in sprinklered buildings is not necessary provided that:

1. the steel structures meet the design and detailing requirements described in this report which lead to dependable response if exposed to adverse fire conditions (see section 9.6 herein)

2. The structures are within the scope of this report as outlined in section 0

Therefore, this passive fire protection need not be applied unless there are other performance requirements (including those that may be specified by interested parties) which would require this passive fire protection.

New Zealand Building Code Clause B1 Structure contains a performance requirement that buildings shall have a low probability of becoming unstable or collapsing, taking into account conditions likely to affect the stability of buildings, including fire. Clause B1 is reproduced in Appendix A for information. New Zealand Building Code Clause C4 Structural Stability During Fire also contains functional requirements for maintaining structural stability during fire. These are more specific and it is possible for a building design to satisfy all of these but not prevent eventual collapse of the building during fire.

Notwithstanding the suggestion above that the need for passive fire protection is questioned in sprinklered buildings, there is a duty of care and expectation associated with structural performance in fire which relates to the type, size and location of the building concerned. For some structures the performance requirements and consequence of failure may be more stringent than for normal buildings. A tall building in a city centre would not be expected to collapse as a result of fire because of the effect this might have on adjacent buildings and general public amenity. Conversely, for a single storey warehouse on the outer fringes of a city, located remote from property boundaries, eventual collapse may be accepted (provided this is in line with the building owner's expectations).

For buildings and occupancy types for which structural collapse is not acceptable, or where avoiding collapse is desirable and the cost of mitigation is low, it is recommended that specific consideration be given to protecting columns from the effects of fire to maintain building stability and avoid overall collapse. The alternative is to show by specific design that stability is still maintained even without passive fire protection to the columns.

10.4 OTHER SPRINKLER TRADE-OFFS

The outcome described in this report is a function of the efficacy required of the sprinkler system. The sprinkler performance objective varies depending on the specific aim of a fire engineering design. For example, the effectiveness of sprinklers to control smoke (amounts and distribution) is much lower than it is to limit fire severity to avoid instability of structural steel frames. Accordingly, the results of this research and conclusions of this report cannot be directly applied to other areas of fire design in which a sprinkler trade-off may appear justified (in particular, any performance requirement relating to control of spread of smoke).

It is important particularly for semi-prescriptive solutions used as part of a performance based design that due recognition is given for the benefits of providing an automatic sprinkler system. If the perceived benefits are not obtainable in practice then designers may be tempted to overcompensate for this, perhaps optimistically reducing the type or coverage of other fire safety systems (e.g. first-aid fire fighting equipment).

11 FUTURE RESEARCH

There are a number of areas in which future research would produce useful results.

A more detailed assessment of the variation in water pressure, over time, needs to be made to establish vulnerability of those buildings for which current supply pressures are marginal. This aspect of unreliability has not been considered in detail in this research.

Information on specific reliability of pumps taken from New Zealand maintenance records would provide more accurate information on reliability of pumped and boosted sprinkler systems.

One of the biggest influences on sprinkler reliability relates to the time that systems are isolated for alterations. Deriving more accurate data on sprinkler isolation frequency and duration for tenancy alterations, would be helpful, particularly if this can be obtained directly from building owner records.

Much of the input data used in this research assumed single values. The sensitivity of the results could be reviewed by evaluating ranges for input data.

The safety of buildings when steel columns are exposed to fully developed fire conditions needs more detailed consideration. Specific issues include evaluating the particular risk for columns at the lowest levels of tall buildings, associated with excessive deformation or axial shortening due to creep or thermal restraint followed by cooling. This is a matter that is not really affected by the effectiveness of sprinklers, but the consequence of failure needs more detailed consideration.

12 CONCLUSIONS

The reputation that sprinkler systems in New Zealand and Australia are highly effective in controlling fires is justified. This is confirmed by statistics prepared from comprehensive data on sprinkler performance in these two countries. Sprinklers installed in accordance with national standards are very reliable and very effective in preventing uncontrolled fires.

For a specific range of building types and occupancies, as defined in the scope of this report, the annual probability that a fire will grow to reach full development in a sprinklered building in New Zealand is extremely unlikely (less than 1.2×10^{-5}). The probability that an unprotected structural steel frame would suffer loss of stability or collapse due to exposure to such a fire is at least 150 times less likely than exposure to other limit states for which the structure is normally designed to resist.

Provided that the steel structural system is checked to verify its capacity to withstand exposure to high fire temperatures (associated with fully developed fires) and to undergo deformations and corresponding ductility demand at the connections and in the member cross-sections, then there appears to be no reason to apply passive fire protection to the structural steel members in sprinklered buildings. Specific details are presented and referenced in this report (normally this would be satisfied if the structure meets the requirements specified in section 9.6 herein).

Concerns regarding the reliability of town main water supplies and the effect on sprinkler reliability are not well founded. The problem is theoretical but not borne out by the statistics obtained. In cities similar to those for which the data on infrastructure and supply reliability was obtained the probability of lack of water from a town main supply is very low. Therefore, this does not appear to be a significant factor in reducing sprinkler reliability.

Steel framed buildings of modern construction supporting concrete floor slabs do not typically collapse when subjected to fully developed fire conditions, even when the structure does not have passive fire protection. Subject to certain assumptions, this has been confirmed by experimental behaviour, by observation of steel structure behaviour in real fires and by analytical methods. The consequences of exposure to fire in new steel buildings are assumed to be similar to those observed in recent experimental tests and real fires, as specifically reported or referenced herein.

The results of this research do not apply to structural situations where either the behaviour in fire is not well documented or the consequence of structural failure is out of proportion to the risk or cost of mitigation (e.g. lowest level columns in a tall building).

The probability of fire following earthquake and its affect on steel structure does not appear to be quite as high as many people expect. It would also be classified as an extremely unlikely event. Providing passive fire protection to a steel frame to cover this scenario is not justified. Providing an alternative pumped water supply for systems in areas of highly seismicity does provide a measurable benefit if a diesel pump is also provided.

This research is based on sprinkler performance as reported for New Zealand and Australia. Strictly speaking the conclusions apply only to these countries but similarities with design requirements in other countries allow comparisons to be made. Structural limit state design in other countries is often very similar to that in Australasia, particularly with respect to exceedance probabilities if not the detail of the design. However, the performance of sprinkler systems in other countries needs to be critically examined to verify if similar sprinkler reliability is achieved before these conclusions can be applied.

Finally, this report is concerned with the probability of structural collapse. In terms of fire safety, and specifically life safety, the likelihood of multiple deaths caused by fire spread is greater than from structural collapse, so the aspects of fire design discussed herein are not significant contributors to the threat to life safety from fire.

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APPENDICES

APPENDIX A – NZBC CLAUSES B1, C4

NZBC CLAUSE B1 STRUCTURE

This Clause is extracted from the New Zealand Building Code contained in the First Schedule of the Building Regulations 1992.

OBJECTIVE

B1.1 The objective provision is to:

a. Safeguard people from injury caused by structural failure,

b. Safeguard people from loss of *amenity* caused by structural behaviour, and

c. Protect *other property* from physical damage caused by structural failure.

FUNCTIONAL REQUIREMENT

B1.2 *Buildings, building elements* and *sitework* shall withstand the combination of loads that they are likely to experience during *construction* or *alteration* and throughout their lives.

PERFORMANCE

B1.3.1 *Buildings, building elements* and *sitework* shall have a low probability of rupturing, becoming unstable, losing equilibrium, or collapsing during *construction* or *alteration* and throughout their lives.

B1.3.2 *Buildings, building elements* and *sitework* shall have a low probability of causing loss of *amenity* through undue deformation, vibratory response, degradation, or other physical characteristics throughout their lives, or during *construction* or *alteration* when the *building* is in use.

B1.3.3 Account shall be taken of all physical conditions likely to affect the stability of *buildings, building elements* and *sitework,* including:

a. Self–weight,

b. Imposed gravity loads arising from use,

c. Temperature,

d. Earth pressure,

e. Water and other liquids,

f. Earthquake,

g. Snow,

h. Wind,

i. Fire,

j. Impact,

k. Explosion

l. Reversing or fluctuating effects,

m. Differential movement,

n. Vegetation,

o. Adverse effects due to insufficient separation from other *buildings,*

p. Influence of equipment, services, non–structural elements and contents,

q. Time dependent effects including creep and shrinkage, and

r. Removal of support.

B1.3.4 Due allowance shall be made for:

a. The consequences of failure,

b. The intended use of the *building*,

c. Effects of uncertainties resulting from *construction* activities or the sequence in which *construction* activities occur,

d. Variation in the properties of materials and the characteristics of the site, and

e. Accuracy limitations inherent in the methods used to predict the stability of *buildings.*

B1.3.5 The demolition of *buildings* shall be carried out in a way that avoids the likelihood of premature collapse.

B1.3.6 *Sitework*, where necessary, shall be carried out to:

a. Provide stability for *construction* on the site, and

b. Avoid the likelihood of damage to *other property.*

B1.3.7 Any *sitework* and associated supports shall take account of the effects of:

a. Changes in ground water level,

b. Water, weather and vegetation, and

c. Ground loss and slumping.

NZBC CLAUSE C4 STRUCTURAL STABILITY DURING FIRE

This Clause is extracted from the New Zealand Building Code contained in the First Schedule of the Building Regulations 1992.

OBJECTIVE

C4.1 The objective of this provision is to:

a) Safeguard people from injury due to loss of structural stability during fire, and

b) Protect household units and other property from damage due to structural instability caused by fire

FUNCTIONAL REQUIREMENT

C4.2 Buildings shall be constructed to maintain structural stability during fire to:

a) Allow people adequate time to evacuate safely

b) Allow fire service personnel adequate time to undertake rescue and firefighting operations, and

c) Avoid collapse and consequential damage to adjacent household units or other property

PERFORMANCE

C4.3.1 Structural elements of buildings shall have fire resistance appropriate to the function of the elements, the fire load, the fire intensity, the fire hazard, the height of the buildings and the fire control facilities external to and within them.

C4.3.2 Structural elements shall have a fire resistance of no less than that of any elements to which they provide support within the same firecell.

C4.3.3 Collapse of elements having lesser fire resistance shall not cause consequential collapse of elements required to have a higher fire resistance.

APPENDIX B – NZS 4541 SPRINKLER MAINTENANCE REQUIREMENTS

NZS 4541 MAINTENANCE REQUIREMENTS FOR AUTOMATIC SPRINKLER SYSTEMS

Part 12
Routine testing, maintenance and surveying

1201 GENERAL

1201.1
The system shall be maintained in efficient working order. Regular tests and inspections shall be made as specified in this Part to ensure that the building is adequately protected and that the system is in efficient working order. There shall be a testing contract with a listed contractor to ensure that the control and alarm equipment is regularly tested. A sprinkler system shall not be deemed to comply with this Standard unless, after completion of installation, it is tested, maintained and surveyed on a regular basis by a contractor, in the manner set out in this Part and any deficiencies promptly corrected.

To give effect to this requirement, the owner of the sprinkler system shall enter into a contract with a contractor and the form of the contract shall be approved by the authority having jurisdiction.

For the purposes of the routine testing, maintenance and surveying of any hand held fire-fighting equipment deemed part of the system the term "contractor" may include a reputable company that is skilled in, and equipped for, such work and able to provide a continuing service.

1201.2
To check continued compliance with this Standard, the authority having jurisdiction may request permission from the owner to enter the protected premises and to check any or all parts of the system and such request shall not be unreasonably denied.

If the authority having jurisdiction requires any valve, pump, alarm or other device to be manipulated as a part of the check, the owner shall arrange for his contractor to attend and to carry out such operations.

1201.3
A written record of all tests and maintenance shall be made in a form approved by the authority having jurisdiction and copies shall be forwarded monthly to the authority. A further copy shall be retained at the control valves. A full report on each survey shall be sent to both the owner and the authority having jurisdiction.

1202 ROUTINE TESTS AND MAINTENANCE

1202.1 Weekly
The following procedures shall be carried out at a weekly interval:

(a) Diesel engine driven pumps shall be exercised under load for a period of at least 15 minutes and shall be checked for correct start, run and stop functions and for battery, fuel, oil and water levels. (This test shall be carried out twice weekly until the pump unit has run for a total of 50 hours.);

(b) Electric motor driven pumps which do not have the power supply to them continuously monitored by an approved audible alarm device, shall be exercised under load for a period of at least 5 minutes and shall be checked for correct start, run and stop functions;

(c) The correct operation of duplex time spaced pulse (Mark VIII) fire brigade alarms shall be checked.

1202.2 Monthly

The following procedures shall be carried out at not longer than monthly intervals:

(a) The brigade isolate switch shall be operated;

(b) The correct operation of every input into the fire brigade alarm signal generator including pressure switches and anti-interference alarms and the correct operation of the fire brigade alarm signal generating unit shall be checked;

(c) All chains, locks and straps shall be checked;

(d) The hydraulic gong shall be exercised and if necessary, oiled;

(e) Every stop valve on the water supplies, other than street valves, shall be checked to ensure that it is open, correctly marked and secured;

(f) The control valves, and the area immediately around them in the valve house, shall be checked for free access and if necessary, cleared. If free access cannot be achieved the situation shall be reported to the building owner and noted in the report;

(g) The installation pressure and the water supply (no flow) pressures shall be checked for adequacy and recorded. In the event that supply pressures are less than the static reference pressures, a flow test in accordance with 1202.3(d) shall be undertaken;

(h) Electric motor driven pumps which have their power supply monitored by an approved audible alarm device, shall be exercised under load for a period of at least 5 minutes and shall be checked for correct start, run and stop functions, delivery and suction pressure, and for correct operation of the monitoring device;

(j) Diesel engine driven pumps shall be checked for battery acid density, battery age, external cleanness, belt tightness, filter state, and correct spare parts inventory;

(k) Any static water supply shall be checked and the level recorded. If the level is less than required the building owner shall be notified and the report annotated to that effect.

1202.3 Quarterly

The following procedures shall be carried out at not longer than quarterly intervals:

(a) The installation pressure of each installation shall be dropped by means of the drain valve and the operating pressures of the fire brigade alarm and hydraulic gong checked and recorded. The correct operation of the hydraulic gong shall also be checked;

(b) All street valves shall be visually inspected to ensure accessibility and manually operated to check that they are fully open;

(c) The hose reel water supply shall be checked (if applicable);

(d) Each water supply shall be separately tested through the 50 mm drain valve (or substitute device) to determine whether there has been any deterioration compared with the water supply reference pressures displayed at the control valves.

This may be carried out in the following manner using the graph in figure 2.2:

(i) Plot the static pressure on the zero flow line of the graph

(ii) Plot the intersect of the drain test curve with the installation pressure when the drain valve is fully open

(iii) Draw a line between points (i) and (ii)

If this line is substantially below the reference flow line investigate the cause.

If any design requirement is above this line record the water supply as being inadequate, and initiate procedures to have it restored to good working order.

NOTE –

(1) Where the drain valve is used for this test, because of the comparatively low flow from a 50 mm orifice, a significant deterioration in the water supply may produce only a minor reduction in residual pressure. It is therefore essential to use accurate gauges and to read and record the gauges with great care.

(2) This test should be regarded as indicative. In the event of a reduction in pressure below the reference pressure:

(i) The water supply should be regarded as being defective and the fact reported IMMEDIATELY to the authority having jurisdiction unless the defect can be remedied forthwith

(ii) A full water supply test is to be carried out using the fire sprinkler inlet (or substitute device).

(3) On diesel engine driven pumps, tachometer readings should be made in conjunction with these pressure readings. A decrease in engine speed could indicate a reduction in engine power output and an increase could indicate a reduction in pump output.

(e) In-line water strainers shall, after any full design flow tests, be removed and cleaned. Flushing is not acceptable.

(f) Each subsidiary stop valve and its supervisory system shall be checked to ensure correct operation, and that the valve is open, correctly marked and secured. Amdt 1 Dec '97

1202.4 Yearly and four-yearly checks

The following procedures shall be carried out at the frequency specified:

(a) All hand operated fire fighting appliances installed to comply with this Standard shall be tested annually along with such other checks as are specified in NZS 4503;

(b) Each battery of every diesel engine driven pump set shall be routinely replaced every 4 years except that one of the batteries shall be initially replaced after 2 years so that, thereafter, one battery is replaced every 2 years

NOTE – In this context "battery" means a set of cells connected to a single charger.

(c) Every diesel engine forming part of a diesel engine driven pump unit shall be serviced by the engine manufacturer's agent every year, the oil changed, and a check made of the air filter, the coolant for corrosion, and the fuel for bacterial sludging.

Additionally, every second year, the service shall include changing the oil filters, fuel filters, belts and thermostats. This service shall be followed by a full load run of the pump unit for at least 2 hours.

(d) The alarm valve, main stop valve, drain valve and water supply check valves shall be overhauled four-yearly;

(e) Every water supply tank shall be checked four-yearly for cleanness and, if necessary, emptied and cleaned out;

(f) Check valves forming part of tail end anti-freeze installations and the density of the anti-freeze solution shall be checked at least annually;

(g) Flow switches and their associated panel indicators shall be tested annually using the test facility described in 406.4;

(h) Concealing plates of retracted deflector/concealed sprinklers shall be removed annually, cleaned and checked;

(j) All surfaces of fire walls which provide separation between sprinklered and unsprinklered firecells or between sprinklered and unsprinklered buildings shall be inspected to confirm that the wall has not been perforated or its integrity impaired. Such inspections shall be made annually for non-masonry fire walls and at intervals not exceeding 2 years for masonry firewalls.

Amdt 1 Dec '97

(k) Check valves forming part of the water supply arrangement of a system being supplied with potable water shall be tested annually for leakage according to the procedure specified in G12 of the New Zealand Building Code or by some other approved method.

1202.5
In addition to the tests specified in the preceding subsections, the authority having jurisdiction may specify such other tests as may be necessary for non-standard types of systems.

1203 ROUTINE SURVEYS

1203.1
It is important that a sprinkler system at all times complies with this Standard in all respects. To ensure that building alterations, changes in process or storage patterns or progressive deterioration of system components do not leave the system out of compliance, a comprehensive survey shall be carried out biennially at intervals not exceeding 28 months. Such surveys shall be carried out by a contractor.

1203.2
The routine survey shall include checks on the following matters with respect to compliance with this Standard:

(a) The separation between protected and unprotected areas and the presence of, and separation for, exposure hazards;

(b) The adequacy of the design density for the hazard present at the time of the survey;

(c) The adequacy of sprinkler spacing throughout the protected area;

(d) The adequacy of clear spaces below sprinklers;

(e) The adequacy of in-rack protection or in-rack bulkheads with respect to racking layouts present at the time of the survey;

(f) The operation, labelling and securing of all valves, controls, pumps, tank filling, supervisory signalling and indicating devices, and any other equipment which forms part of the sprinkler system;

(g) The accessibility, functioning and labelling of the fire sprinkler inlet;

(h) The accuracy within ±3 % of all pressure gauges at normal supply pressure when checked against a test gauge certified to Part 2 of BS 1780;

(j) The adequacy of all fire rated partitions required in accessible concealed spaces from which sprinklers have been omitted;

(k) The adequacy of all storage height limitation signs;

(m) The density of anti-freeze installations and the adequacy of separation barriers;

(n) The operation of any interlock required with machinery or equipment external to the sprinkler system;

(o) The currency of the block plan, emergency instructions and "sprinkler stop valve inside" indicator plate;

(p) The operation, flow and pressure characteristics of each water supply with respect to the performance at the time of initial installation and the design flow and pressure at the time of survey;

(q) Confirmation that the weekly, monthly and quarterly tests have been adequately carried out since the last survey;

(r) Confirmation that hand operated fire fighting equipment has been tested and maintained in accordance with NZS 4503;

(s) Confirmation that the actual opening pressure differential ratio for the alarm valve complies with 404.4.1.

1203.3
The report shall indicate the items inspected and the results of all tests and additionally shall specifically provide the following information:

(a) The method of separation between protected and unprotected areas;

(b) The required design density and area of operation for each area of the building and the height of the highest sprinkler in each area;

(c) The required design flows and design pressures at the time of the survey;

(d) An hydraulic sketch of each water supply as tested, with the design flows and pressures marked;

(e) A list of all matters which require remedy in order to maintain compliance with this Standard.

APPENDIX C - FIRES FOLLOWING EARTHQUAKE

FIRES FOLLOWING EARTHQUAKE; PROBABILITIES USED IN EVENT TREE ANALYSIS

Fires following earthquake

Probabilities used in event tree analysis

sub-system Outcomes: F =favourable; U =unfavourable

sub-system		outcome			P()		P()		P()
Class A water supply			1.000						
P(F)	P(U)	F	0.324	sprinkler pipework OK	0.6	tank full	0.9	diesel pump operates	0.6
0.32	0.68	U	0.216	sprinkler pipework faulty	0.4	tank full	0.9	diesel pump operates	0.6
		U	0.036	sprinkler pipework OK	0.6	tank not full	0.1	diesel pump operates	0.6
		U	0.024	sprinkler pipework faulty	0.4	tank not full	0.1	diesel pump operates	0.6
		U	0.216	sprinkler pipework OK	0.6	tank full	0.9	diesel pump does not operate	0.4
		U	0.144	sprinkler pipework faulty	0.4	tank full	0.9	diesel pump does not operate	0.4
		U	0.024	sprinkler pipework OK	0.6	tank not full	0.1	diesel pump does not operate	0.4
		U	0.016	sprinkler pipework faulty	0.4	tank not full	0.1	diesel pump does not operate	0.4
Class B/C water supply			1.000						
P(F)	P(U)	F	0.012	sprinkler pipework OK	0.6	town main OK	0.2	electricity available for pump	0.1
0.01	0.99	U	0.008	sprinkler pipework faulty	0.4	town main OK	0.2	electricity available for pump	0.1
		U	0.048	sprinkler pipework OK	0.6	town main not OK	0.8	electricity available for pump	0.1
(no pump)		U	0.032	sprinkler pipework faulty	0.4	town main not OK	0.8	electricity available for pump	0.1
P(F)	P(U)	U	0.108	sprinkler pipework OK	0.6	town main OK	0.2	electricity not available for pump	0.9
0.12	0.88	U	0.072	sprinkler pipework faulty	0.4	town main OK	0.2	electricity not available for pump	0.9
		U	0.432	sprinkler pipework OK	0.6	town main not OK	0.8	electricity not available for pump	0.9
		U	0.288	sprinkler pipework faulty	0.4	town main not OK	0.8	electricity not available for pump	0.9

sub-system		outcome			P()		P()
Passive fire protection			1.000				
P(F)	P(U)	F	0.9025	fire prot remains in place	0.95	fire protection installed correctly	0.95
0.903	0.098	U	0.0475	fire prot damaged	0.1	fire protection installed correctly	0.95
		U	0.0475	fire prot remains in place	0.95	fire protection installed incorrectly	0.05
		U	0.0025	fire prot damaged	0.1	fire protection installed incorrectly	0.05

Earthquake occurs

P(F)	P(U)
0.998	0.002

Outbreak of fire

P(F)	P(U)
0.90	0.10

Fire reaches flashover

P(F)	P(U)
0.30	0.70

Fire controlled by sprinklers

P(F)	P(U)
0.99	0.01

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